Ann. Rev. Astron. Astrophys. 1978. 16: 103–39

THE KINEMATICS OF SPIRAL AND IRREGULAR GALAXIES

*2127

P. C. van der Kruit and R. J. Allen
Kapteyn Astronomical Institute, University of Groningen, Groningen, The Netherlands

1 INTRODUCTION

The rotation of spiral nebulae was recognized by Wolf (1914) in M81 and Slipher (1914) in M104 from the inclination of the stellar absorption lines on spectra of the central regions, although the identification of these nebulae as disk galaxies was at that time controversial. That the discovery was made first with absorption lines instead of the more readily observable emission lines can be attributed to observational selection: the central regions of the nebulae were brightest, and the presence there of absorption lines had been known for a long time (e.g. Scheiner 1899). However, we now know that these same central areas are often deficient in the H II regions responsible for the emission lines. The step from rudimentary measurements of rotation in the central regions to a map of the radial velocity field over the whole image of a galaxy has proven to be a laborious one, requiring a combination of modern optical and radio methods of observation. For the same two galaxies in which the original discovery of the rotation using the absorption lines was made 65 years ago, it is only recently that reasonably complete pictures of the distribution of radial velocities have been constructed (e.g. Münch 1959, Rots 1974, Faber et al. 1977).

The first observations to result in a plot of the radial velocity versus radius were made by Pease (1916, 1918) for M31 and M104. It was a tedious business, with exposure times of about 80 hours for each absorption spectrum, but the results on M104 showed that the radial velocities relative to the center increased linearly with radius, reaching more than 300 km sec^{-1} at a distance of 2$'$.5. Pease's measurements along the minor

0066-4146/78/0915-0103$01.00

axis of M31 indicated that the radial velocity was nearly constant at all positions, showing that the variation observed along the major axis "... is without doubt to be attributed to the rotation of the nebula." Although Pease's rotation curve of M104 does not agree too well with recent determinations (Faber et al. 1977, Schweizer 1978), his achievement is remarkable considering the relatively primitive instrumentation available to him at the time.

Emission lines from H II regions in the spiral nebulae were discovered about the same time as "nebular rotation." Pease (1915) recorded [OIII] λ 5007, Hβ, and Hγ in a $34\frac{1}{2}$-hour exposure of NGC 604 in M33, and Slipher (1915) also detected emission lines in this object. However, for many years emission lines remained of limited use in studies of the rotation of galaxies; although exposure times were significantly shorter, a single spectrum provided at most only a few measured points in the galaxy owing to the discrete nature of the H II regions. In his classical study of the rotation of M31, Babcock (1939) determined 44 velocity measurements in the inner regions from 236 hours of exposure on the absorption lines; an additional 56 hours of exposure on emission lines yielded only 4 more points. These 4 points were, however, very important, for they permitted extension of the rotation curve a factor of 3 further out into the main part of the disk. Later Mayall (1951) increased the emission line observations of M31 to 32 H II regions. Mayall & Aller (1942) managed to observe the emission lines in M33 with up to three H II regions per exposure using a judicious choice of slit orientation; nevertheless, 25 data points required 311 hours of observations. Even the advent of modern image tubes has not led to a very spectacular reduction in the observing time; the detailed study of the H II region velocities in M31 by Rubin & Ford (1970) still required almost 112 hours of exposure for 67 data points.

Galaxies of smaller angular size are clearly more amenable to the trick of placing several H II regions in the spectrograph slit, and the long-slit techniques employed by Babcock (1939) and by Mayall (1948, 1951) were applied to such galaxies in particular by Burbidge and Burbidge (see Burbidge & Burbidge 1975 for a review). The slit was usually oriented along the major axis of the galaxy, so that the H II regions produce emission lines over a large radial extent on a single spectrum. The use of emission lines has the further advantages that the measurements are more accurate and refer to a discrete position in the plane of the galaxy rather than an average along the line of sight. This method has yielded good rotation curves usually from only a few spectra taken near the major axis of each galaxy, often with a check from spectra near the minor axis. The procedure requires 10–20 hours of exposure. It is of course not applicable to the early-type galaxies, which are deficient in H II regions.

Determination of the velocity field over the entire disk of a galaxy would provide important additional information; the amount and extent of noncircular motions would be more clearly revealed, and the orientation parameters could be determined from the velocity field itself rather than from the distribution of broad-band light over the galaxy. The use of modern, fast image tubes (e.g. van der Kruit 1976b) permits long-slit spectra to be obtained in many position angles without requiring exorbitant amounts of telescope time. Fabry-Perot interferometers (Courtès 1960) are beginning to provide detailed data over the relatively larger fields of the more nearby galaxies with only a few hours of exposure (e.g. Tully 1974a), although the reduction of the interferograms is lengthy and complicated in comparison with the relatively straightforward treatment of long-slit spectra.

It has been known for some time that the neutral hydrogen gas in late-type galaxies extends to relatively large radii (e.g. Roberts 1972), so that mapping of the H I velocity field would provide not only independent but also complementary information on the kinematics. The complementarity of the radio–H I observations is further reinforced by two other limitations. First, the relatively lower angular resolution of radio telescopes prevents useful measurements in the central regions of galaxies where the large-velocity gradients are smoothed over the telescope beam. Second, many intermediate-type galaxies (e.g. M31, M81) have little H I in the central regions anyway. The velocity fields in the central regions of most galaxies can therefore be measured at present only by optical means; on the other hand, the H I observations provide information at larger radial distances where much of the total mass and most of the angular momentum is to be found. The complementarity is further useful in more detailed studies of the kinematics of spiral arms: H II regions are often grouped in long, thin structures defining the arms, so that it is difficult to measure emission-line velocities between the arms. However, sufficient neutral gas is usually present between the spiral arms to permit reliable velocity measurements of the H I there.

The first detailed observations of the H I in M31 were made by van de Hulst et al. (1957) using the 25 m Dwingeloo radio telescope with an angular resolution of 0°6. The measurements resulted in a rotation curve from 0°6 to 2°5 from the center, a significant extension beyond the 1°5 radial distance of Babcock's last point. With a similar angular resolution but improved receiving equipment, Argyle (1965) measured H I profiles over the whole image of M31 and was the first to plot a complete radial velocity field for any galaxy. Modern aperture-synthesis radio telescopes now provide the angular resolution (0′5–1′0) needed to separate spiral arms in the largest galaxies out to distances of about 5 Mpc, and are also sufficiently sensitive to study the larger-scale kinematics of many more systems at greater distances.

The radio-synthesis maps that have been published in the last few years have required of the order of 200 hours of observing time per galaxy; however, as is also the case at optical wavelengths, the newest instrumentation now coming into operation promises to reduce the time taken at the telescope by as much as a factor of 10.

In this chapter we review the present status of kinematical studies of intermediate- and late-type galaxies. We do not discuss results on E or S0 galaxies, nor the details of velocity dispersion measurements in the central regions of spirals. The emphasis is on observations that result in extensive maps of velocity fields rather than determinations of rotation curves from major axis observations only. Earlier discussions on several topics covered in this review have been given by Oort (1974) and Allen (1975a), and the interpretation of the kinematical information in terms of galaxy dynamics has been reviewed by Burbidge & Burbidge (1975), de Vaucouleurs & Freeman (1973), Freeman (1975), Roberts (1975b), and Toomre (1977). We believe our literature list to be complete up to September 1977, including preprints that were available to us at that time.

2 MEASUREMENT OF THE DISTRIBUTION AND KINEMATICS OF THE GAS

When one applies the restriction that observations should provide information over an appreciable fraction of the galaxy disk, one finds that there are relatively few published results from absorption-line measurements of the stellar component. In this section we therefore concentrate on the available data for the gas and compare the results obtained from the various methods of observation.

In Table 1 we list references to observations that satisfy the selection criteria. References to emission-line slit-spectra are limited to those resulting in velocity data extending over a large part of the galaxy image. The Fabry-Perot data provide such information in a single observation, so the reference list is intended to include all papers on those results. References to radio–H I data are restricted to those providing the highest relative resolution; information on the general characteristics of the H I distribution and velocity field require beamwidths of at most about one-tenth of the Holmberg diameter, and even higher resolution is needed in order to separate spiral arms (Allen 1975a). References to earlier work (prior to about 1969) and to less extensive observations of galaxy kinematics can be found in the reviews by Burbidge & Burbidge (1975) and by Roberts (1975a,b), in the I.A.U. Reports on Astronomy for

Table 1 List of galaxies for which the velocity field has been measured by sampling many points over a large fraction of their disks

NGC	Type	Slit spectra of optical emission lines	Hα Fabry-Perot interferometry	H I 21-cm observations with good resolution
224 (M31)	Sb	Rubin & Ford 1970, 1971	Deharveng & Pellet 1975a, b	Argyle 1965 Roberts 1966 Davies & Gottesman 1970 Gottesman & Davies 1970 Guibert 1973, 1974 Emerson 1974, 1976 Roberts & Whitehurst 1975 Roberts et al. 1978 Shane 1978 Newton & Emerson 1977
253	Sc	Demoulin & Burbidge 1970 Ulrich 1978	Deharveng 1971	Combes et al. 1977
300	Sd			Shobbrook & Robinson 1967
598 (M33)	Scd	Mayall & Aller 1942	Carranza et al. 1968 de Vaucouleurs & de Vaucouleurs 1971	de Jager & Davies 1971 Gordon 1971 Wright et al. 1972 Warner et al. 1973 Huchtmeier 1973 Rogstad et al. 1976
628	Sc		Monnet & Deharveng 1977	
1068	Sb	Walker 1968		
1569	Irr		de Vaucouleurs et al. 1974	
2043	Scd		Deharveng & Pellet 1970	Burns & Roberts 1971 Shostak & Rogstad 1973 Shostak 1973
2685	Spec	Ulrich 1975		Shane 1977 Shane & Bystedt 1978
2715	Sc	van der Kruit & Bosma 1978b		
2782	Sb	van der Kruit 1977b		
2841	Sb			Bosma 1978b
2903	Sbc	Simkin 1975a		
3031 (M81)	Sab	Goad 1974, 1976		Rots & Shane 1975 Rots 1975 Gottesman & Weliachew 1975 Allen 1976
3067	Sab	Danziger & Chromey 1972		
3079	SBc	Carozzi 1977		
3198	Sc			Bosma 1978b
3310	Sbc, pec	van der Kruit 1976a		
3351	SBb	Rubin et al. 1975 Peterson et al. 1976		
3359	SBc			Siefert et al. 1975
3675	Sb	van der Kruit 1975		
4027	SBd	de Vaucouleurs et al. 1968		
4151	Sab	Simkin 1975b		Bosma et al. 1977a
4236	Sm			Shostak & Rogstad 1973
4258	Sbc	van der Kruit 1974b	Courtès 1972	van Albada & Shane 1975
4449	Irr		Crillon & Monnet 1969a	van Woerden et al. 1975
4490/85	Irr		Boulesteix et al. 1970	
4631	Sd		Crillon & Monnet 1969b	Winter 1975, Weliachew et al. 1978
4736	Sab	van der Kruit 1974a, 1976c		Bosma et al. 1977b
5033	Sc	van der Kruit & Bosma 1978b		Bosma 1978b
5055	Sbc	van der Kruit & Bosma 1978b		Bosma 1978b
5194 (M51)	Sbc	Burbidge & Burbidge 1964	Carranza et al. 1969 Tully 1974a	Weliachew & Gottesman 1973 Shane 1975 Segalovitz 1976
5236 (M83)	Sc			Rogstad et al. 1974
5383	SBb	Peterson et al. 1978		Allen et al. 1973a
5457 (M101)	Scd		de Vaucouleurs & de Vaucouleurs 1971	Rogstad & Shostak 1971 Rogstad 1971 Allen et al. 1973a, b Allen 1975a, b, 1976

Table 1 (*continued*)

NGC	Type	Slit spectra of optical emission lines	Hα Fabry-Perot interferometry	H I 21-cm observations with good resolution
6574	Sbc	Demoulin & Tung Chan 1969		
6946	Scd			Rogstad et al. 1973
7331	Sb			Bosma 1978b
7640	Sc			Seielstad & Wright 1973
LMC[a]	SBm		Georgelin & Monnet 1970 Carranza et al. 1971 Smith & Weedman 1971 Chèriguène & Monnet 1972	McGee & Milton 1966
SMC[b]	Irr	Feast 1970	Carranza et al. 1971 Smith & Weedman 1973	Hindman 1967 Erkes et al. 1973
IC10	Irr			Shostak 1974
IC342	Scd			Rogstad et al. 1973
IC2574	Sm			Seielstad & Wright 1973
Holm I	Irr			Tulley et al. 1978
Holm II	Irr			Cottrell 1976b
DDO 125	Irr			Tully et al. 1978
Maffei II	Sb?			Shostak & Weliachew 1971 Love 1972

[a] Detailed kinematical studies of the LMC have also been made for the planetary nebulae (Smith & Weedman 1972), blue globular clusters (Andrews & Evans 1972), and supergiants (Prévot 1973).
[b] A detailed kinematical study of the SMC has also been made for the supergiants (Dubois 1975).

Commission 28, in the circulars of the I.A.U. Working Group on Internal Motions in Galaxies, and, in the case of the LMC and SMC, in the proceedings of a conference on "The Magellanic Clouds" (Muller 1971). Observations of kinematics in the nuclear regions are referenced by Burbidge (1972) and Ulrich (1974), and are briefly discussed in Section 4.1 below.

2.1 *Methods of Observation*

The methods of observation and reduction of long-slit spectra have been discussed by Burbidge (1962), for example, and reviewed by Burbidge & Burbidge (1975). A recent analysis of the reduction procedures and the resulting accuracy has been published by van der Kruit (1976b), with particular attention given to the well-known correction for the curvature of the slit image on the spectrogram (Minkowski 1942) and for other distortions due to the image tube. With dispersions of about 50 Å mm^{-1}, a precision of 10 km sec^{-1} or better is possible. Schweizer (1975) has called attention again to effects of asymmetric illumination of the slit and pointed out that the resulting distortions on the spectra may not always be negligible, especially at lower dispersion. Simkin (1975a) found zero-point shifts of up to 100 km sec^{-1} that varied with the orientation of the spectrograph during the observations. Such shifts are apparently not always present, however, since in other cases (e.g. Rubin & Ford 1970, 1971, Goad 1976, van der Kruit 1976b, van der Kruit & Bosma 1978b) checks of internal consistency and a comparison of the results of various optical and H I observations on the same object suggest zero-point errors of at most a few km sec^{-1}.

The application of Fabry-Perot interferometric methods to observations of the emission lines and the treatment of the resulting interferograms are described in detail by Courtès (1960, 1964) and more recently by Tully (1974a). Tully paid particular attention to distortions and to the the deconvolution of the instrumental and intrinsic spectral profiles; he concludes that measurements of radial velocities with these techniques can be made with an accuracy of 10 km sec^{-1}, which is comparable to that obtained from slit spectra.

The problem with radio observations of the distribution and motions of H I has mainly been the insufficient angular resolution of diffraction-limited radio telescopes. Useful information on several nearby galaxies of large angular size has been obtained from observations with the world's largest single-dish instruments: the 300-ft telescope at Green Bank, the 100-m telescope at Effelsberg, and most recently the Arecibo 1000-ft telescope. The methods of observation and some notable results have been described by Roberts (1975b), Roberts et al. (1978), and Huchtmeier (1975). For most galaxies, however, angular resolution even better than the $3'-10'$ provided by these instruments is needed, and the majority of the H I maps discussed here have been made with aperture-synthesis radio telescopes: the two-element interferometer at Owens Valley (e.g. Rogstad & Shostak, 1971), the half-mile radio telescope at Cambridge (Baldwin et al. 1971), and the synthesis radio telescope at Westerbork (Allen et al. 1974). There are many instrumental problems peculiar to these data, and some of the difficulties associated with nonuniform coverage of the aperture plane, side-lobe effects, missing short-baseline information, subtraction of continuum emission, and analysis of the H I profiles are discussed by, for example, Rots (1974), Schwarz (1978), and van der Hulst (1977). The final accuracy with which the beam-smoothed radial velocity of the H I can be mapped is of the order of a few km sec^{-1}.

2.2 *Distribution of the Gas*

Although it is not the main subject of this chapter, we review briefly the results obtained on the distribution of the gas, since they bear on the radial velocity measurements to be discussed later. Observations of the optical emission lines obviously require the presence of ionized gas, either in discrete H II regions, or, in favorable cases, in the more tenuous areas between them. Hodge (1974a) has reviewed the available information on the radial distribution of H II regions: the surface number-densities are small in the central areas of intermediate- and later-type galaxies, increase to a maximum, then decrease again to small values near the optical boundaries as seen on, for example, the Palomar Sky Survey. The deficiency of H II regions in the central areas is in general correlated with the relative decrease in the H I surface density there (Roberts 1972, Davies 1972), which supports the widely held view that star formation is less vigorous in regions of lower gas density. Oort (1974) and Shu (1974) have suggested that the central depression is a result of accelerated depletion of the gas by star formation due to more frequent passages of the gas through the density wave in the inner regions. A detailed application of this idea to the observations shows a general agreement for M51 (Shane 1975) and to a lesser extent for M81 (Segalovitz 1975).

For several spiral galaxies of large angular size the angular resolution of the radio H I synthesis maps is sufficient to separate spiral arms from each other. The situation for M31, M33, M51, M81, and M101 has been reviewed by Allen (1975a); in all these systems the H I distribution shows spiral structure associated with the optical morphology in a general way. In M51 the H I arms are slightly but systematically displaced from the Hα arms, coinciding instead with the dust lanes (see also Shane 1975), as is also the case for M81 (Rots 1975). The displacement has been interpreted in terms of migration of newly formed stars away from the region of the shock in the density-wave model for spiral-arm structure described by Roberts (1969).

The correlation of H I with H II becomes more complicated when one looks in greater detail: Boulesteix et al. (1974) have pointed out that although on the kiloparsec scale the H II region number densities correlate with regions of higher-than-average H I gas density in M33 (see also Israel & van der Kruit 1974), on a smaller scale one finds that most of the H II regions are in fact situated near the edges of dense H I concentrations. Emerson (1974) has found a similar situation in M31. He offers further the suggestion that the effect is only an apparent one, caused by obscuration of H II regions embedded within the H I clouds by the greater concentrations of dust probably present there. On the other hand, Allen (1975b) has called attention to the existence of a contrasting situation for the giant H II complexes in M101; although dust is known to be present within them (Israel et al. 1975), the optically bright complexes coincide with the brightest areas on the radio H I maps. The explanation probably involves a high degree of inhomogeneity of the dust, H I, and ionized gas in these giant complexes, and much detailed structure will most likely appear when the H I can be measured with even higher angular resolution. Baldwin (1976) noted that the radio maps of M33 and the LMC show no thermal sources that are not identified with an H II region and are at the same time coincident with a peak in the H I distribution; he concludes from this that no luminous H II regions can be hidden by dust.

Accurately calibrated maps of the distribution and motions of the ionized gas in spiral galaxies would provide the basis for quantitative comparison with radio-synthesis observations. As far as we know the only example presently available is the Hα map of M51 presented by Tully (1974a) and used by Segalovitz (1976, 1977) and van der Kruit (1977a) in a new discussion of the radio continuum emission (see also van der Kruit 1978).

2.3 *Velocity Fields*

The general pattern of the velocity fields derived from the observations listed in Table 1 is always dominated by rotation (see Figures 3–7), even for galaxies that appear optically to be very nearly face-on (e.g. NGC 628) or irregular (e.g. NGC 4449, IC 10). Roberts (1975b) has stressed that galaxies of all types show rotation, and it is especially noteworthy that this statement applies even to dwarf irregulars (Cottrell 1976b, Tully et al. 1978). Interpretation in terms of rotation curves is reviewed in Section 3 below.

More detailed examination shows that the observed velocity fields frequently show deviations from the symmetry expected from purely circular rotation, and that these deviations can also be large (e.g. NGC 3310, van der Kruit 1976a). Interpretation in terms of bars and oval distortions, warps, density waves, and nuclear explosions is reviewed in Section 4.

It is evident from Table 1 that there are a number of galaxies for which both optical and radio kinematical data exist. For a few systems there is enough resolution in the H I data to make a detailed comparison with the optical results in the regions of overlap. In M31 the agreement is in general very satisfactory (within about 5 km sec^{-1}, Emerson 1976), as is the case in M33 (Boulesteix & Monnet 1970, de Jager & Davies 1971, Warner et al. 1973) and the LMC (Feast 1970, Smith & Weedman 1971, Chériguène & Monnet 1972). For M81 the agreement is also good (Rots 1975). The velocities of the H I and H II are also similar to those of planetary nebulae (Smith & Weedman 1972), blue globular clusters (Andrews & Evans 1972), and supergiants (Prévot 1973) in the LMC. The situation is, however, somewhat confused in the SMC (Smith & Weedman 1973).

Differences of 10–20 km sec^{-1} for particular objects in M33 may be ascribed to peculiar motions within the H II regions themselves (Warner et al. 1973, Wright 1971) or to the effects of uneven internal obscuration of the light by the dust that must be present there (e.g. van der Kruit & Allen 1976). One must also keep in mind that the radio H I results have inevitably been smoothed by the telescope beam.

The extensive velocity fields of M51 derived from Hα Fabry-Perot interferograms by Tully (1974a) and from radio–H I synthesis by Shane

(1975) are very similar. The orientation parameters and rotation curves obtained from the Hα data by Tully (1974b) and from the H I data by Segalovitz (1976)[1] agree within the uncertainties when one considers the complexity of the velocity field and the differing angular resolutions of the two observing methods. The optical data for the giant H II complexes in M101 also show no large differences with the radio–H I measurements.

3 THE GENERAL ROTATION

As has been mentioned above, the velocity fields determined from optical emission lines and from radio–H I data are almost always dominated by the pattern indicative of circular rotation. This applies, of course, to the gas; before going on to discuss these results further in terms of the dynamical properties of galaxies we briefly examine the evidence that the motions of the stars are also represented by the same general kinematics. Of course the information on the rotation of the stars derived from optical absorption lines is mostly restricted to the central regions. The existence of rotational motions near the nucleus of M31 has been known for a long time from the work of Babcock (1939). From rather more extensive observations Rubin et al. (1973) contended that in the central region of M31 the stars exhibit a velocity field as complex as that of the gas; however, Pellet (1976) observed that the stars follow a pattern of symmetric rotation. Recent observations extending further out into the disks of several other galaxies provide a less controversial picture: In NGC 4594 (Faber et al. 1977, Schweizer 1978) the rotation curves of the stars and the gas are very similar. Peterson et al. (1976) show that the rotation of the stars in the bar of NGC 3351 is consistent with that of the gas in the arms emerging at the ends of the bar. Besides the general rotation, local noncircular motions in the stars have been reported in M51, NGC 5866, and NGC 2903 by Simkin (1970, 1972, 1974, 1975a), but these always seem to be associated with dust patches and other details of the spiral structure; these results probably refer to recently formed stars, since Balmer absorption lines are prominent. We can conclude that as yet there is no strong evidence for a major difference in the large-scale kinematics of the gas from that of the stars.

The assumptions necessary to derive a rotation curve $V_{\mathrm{rot}}(R)$ from the observed velocity field are: 1. the measurements refer to positions on a single inclined plane; and 2. rotation is dominant and all noncircular motions are not part of a large-scale pattern. The procedure is usually to use least-squares numerical schemes (e.g. Warner et al. 1973, van der

[1] The inclination angle quoted by Segalovitz (1976, p. 97) should read 35° and not 15°.

Kruit 1976a) to determine five parameters: position of the rotation center (two numbers), systemic velocity V_{sys}, inclination i of the normal to the galaxy plane with the line of sight, and the position angle ϕ_0 of the line of nodes (major axis). These parameters are determined from different

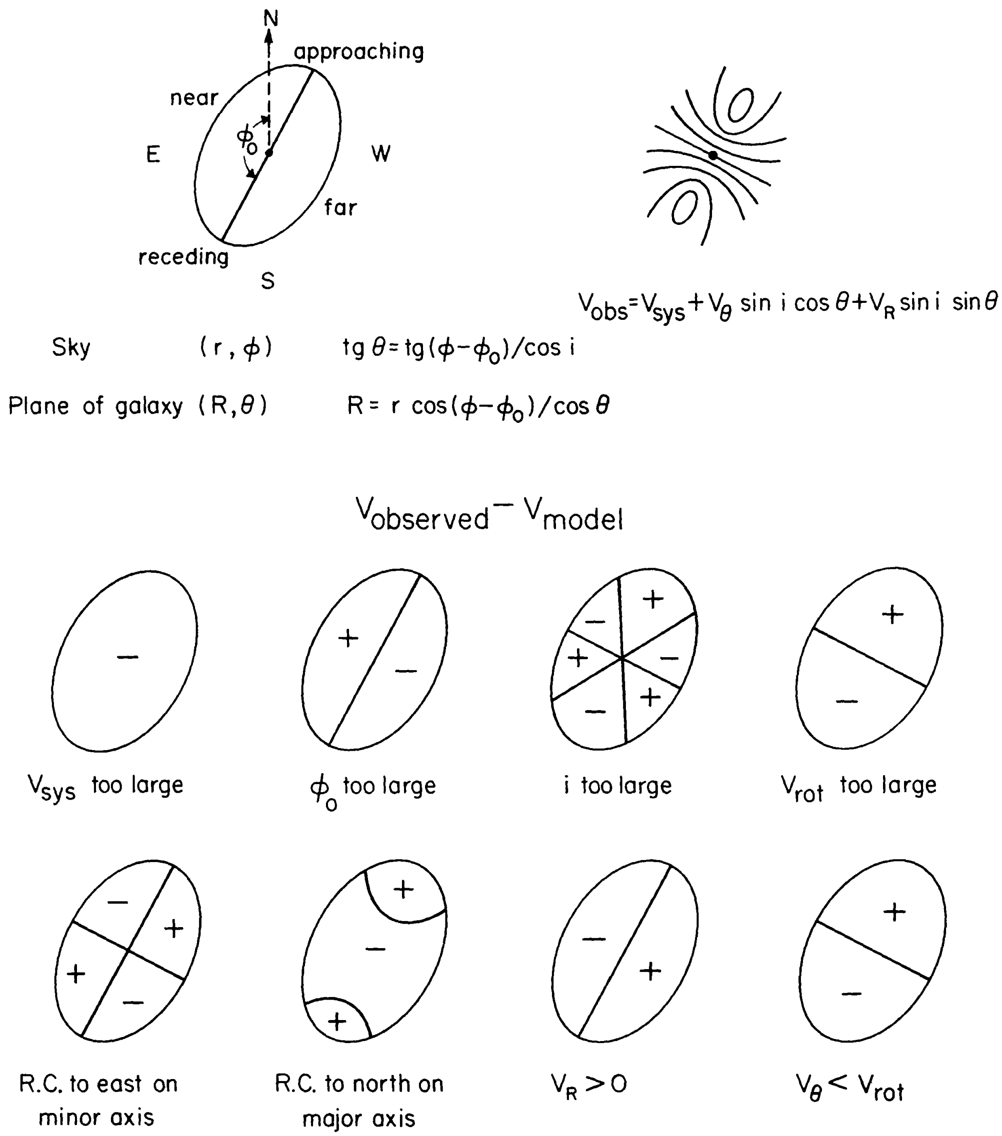


Figure 1 Schematic representation of the rotation of disk galaxies and the determination of dynamical parameters. A galaxy with the orientation at top-left shows a pattern of line-of-sight velocities at top-right, where lines of equal radial velocity are sketched. The contours close around the radius of maximum rotation velocity on the line of nodes. The conversion from observed to intrinsic parameters is given, as is the systematic pattern of residual velocities when all but one of the dynamical parameters are chosen correctly. This representation was first published by Warner et al. (1973). Note that the patterns are different so that these parameters can be fitted independently to the observed velocity field. The last two examples show the effects of noncircular motions in the radial and tangential direction.

symmetry properties of the radial velocity field. The influence of small errors in the parameters is to produce patterns with characteristic symmetries in the diagram of the radial velocity field after subtraction of the nominal rotation curve, was first illustrated by Warner et al. (1973) and is summarized in Figure 1. In particular a systematic pattern of radial expansion or contraction has an effect similar to a change in ϕ_0. Furthermore, deviations in the velocities owing, for example, to a density wave may also perturb the derived rotation curve; a detailed self-consistent model has been used to extract an estimate of the unperturbed rotation curve of M81 by Visser (1978a,b). He finds that the value of V_{max} changes by less than a few km sec^{-1}, but R_{max} decreases from 6 kpc (Rots 1975; see also Figure 2) to 4.8 kpc. Finally, a transverse motion of the galaxy perpendicular to the line of sight produces errors both in ϕ_0 and in $V_{rot}(R)$, but these effects are likely to be small (Warner et al. 1973).

At the end of the numerical procedure the "best fit" rotation curve is available. Various refinements have been used, such as determining i and ϕ_0 as a function of distance from the center by analyzing the velocity field

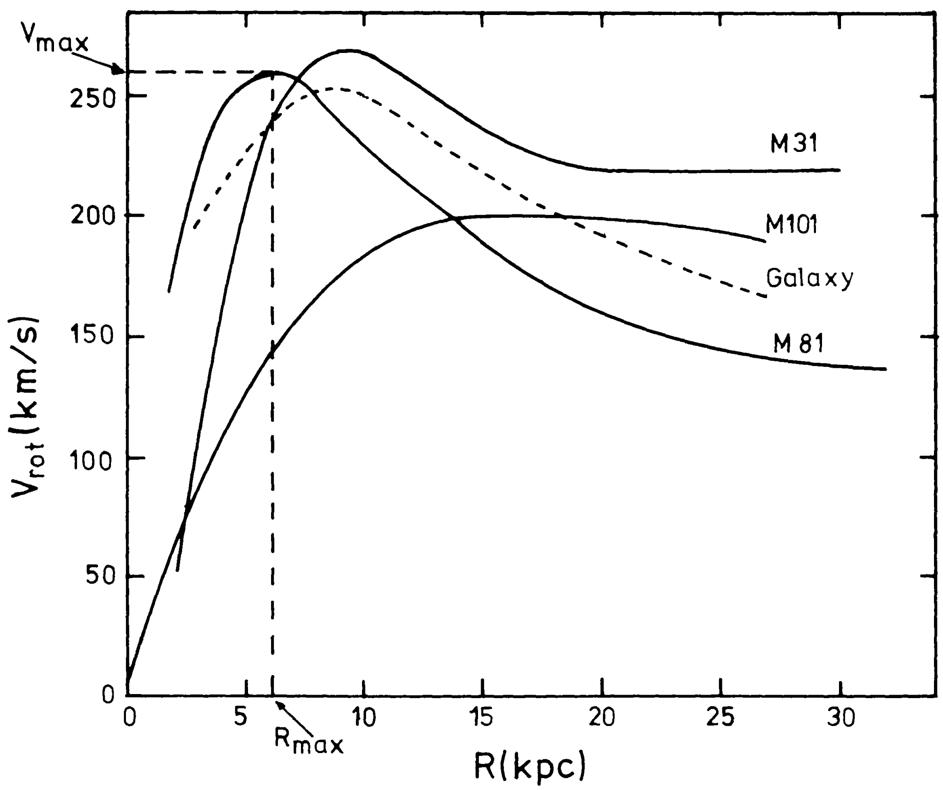


Figure 2 The rotation curves of M31, M101, and M81 according to Roberts & Rots (1973) are shown as solid lines with that for our Galaxy indicated with the dashed line. The parameters R_{max} and V_{max} are indicated for the case of M81 (adapted from Roberts & Rots 1973).

in annular rings, determining the rotation curve separately for the two halves of the galaxy on either side of the minor axis, etc (e.g. Rogstad et al. 1974).

Deviations from circular symmetry often present perplexing problems of interpretation where time-dependent effects must be taken into account. Fortunately, over the main optically bright parts of the disks of most spiral galaxies, these variations and differences are small enough to be treated as perturbations on a uniform circular rotation; however, they do compromise the goal of obtaining reliable mass distributions at large radial distances.

3.1 *Rotation Curve Shape and Galaxy Morphological Type*

Rotation curves determined by the methods outlined above are usually characterized by a rise in the inner regions to some value V_{max} at a radius R_{max}, followed by a slow decline or a more-or-less constant level further out. For a detailed comparison between rotation curves and galaxy morphology one would like to have observational results spanning the range of types and, within each type, the range of luminosities. Needless to say such an extensive sample does not yet exist, although some fragments of it are becoming available. From rotation curves measured over a large part of the optical disks of M81 (Sab), M31 (Sb), and M101 (Scd), as shown in Figure 2, Roberts & Rots (1973) suggested that the mass distributions of Sa galaxies were indeed more centrally condensed than those of the Sc galaxies, as had long been inferred from the distribution of optical light. This characteristic should appear as a faster rise to V_{max}, i.e. a smaller ratio of R_{max} to some other, presumably constant, scale size such as the Holmberg photometric radius R_{Ho}. The ratio R_{max}/R_{Ho} has indeed been found to decrease towards the earlier morphological types in the larger samples of observations made at lower angular resolution (Brosche 1973, Huchtmeier 1975). Shostak (1977, 1978) has determined a relation between the form of the total integrated H I profile and morphological type for galaxies from Sbc to Irr and has suggested that this relation can be understood to be the result of an increase in R_{max} relative to the H I size for the later types. The result is noteworthy also in that it is available from the integrated profiles, i.e. the extreme of no angular resolution at all, where the sample is largest and where observations can be most rapidly obtained.

The correlations described above have been interpreted in terms of the galaxy dynamics by Wakamatsu (1976) in a manner consistent with earlier notions based on the optical appearance of a galaxy; the bulge component becomes progressively more prominent relative to the disk as one moves from the Sc to the Sa galaxies. Although the relation between bulge-to-disk ratio and morphological type is not ideal (van den Bergh 1976), it does seem to hold on the average (Freeman 1970a, Yoshizawa & Wakamatsu 1975, de Vaucouleurs 1977).

We turn now to another dimension of the observations, namely the differing luminosities within each type (see footnote 2). Rogstad & Shostak (1972) analyzed the rotation curves of five Scd galaxies and found a correlation of the maximum rotation velocity V_{max} with the Holmberg radius R_{Ho}. As indicated above, R_{max} scales with R_{Ho} within a particular type. Therefore, if the forms of the rotation curves are reasonably similar, then the total mass of a galaxy (proportional to R_{max}/V_{max}^2) within the Scd type can apparently be characterized by a single parameter. Enlarging the sample any further is again possible only at the expense of giving up angular resolution. Shostak (1975) found for Scd galaxies that the inclination-corrected width of the integrated H I profile $\Delta V(0)$ (which should be close to $2V_{max}$) increases with the linear Holmberg radius.

Tully & Fisher (1977) have discovered an important correlation of $\Delta V(0)$ with total optical luminosity for a sample of galaxies of many types. In an extensive numerical analysis, Brosche (1971) found that V_{max} decreased towards late types and was nearly independent of R_{max} (Brosche 1973). His correlation between V_{max} and type can be understood also as a correlation between V_{max} and luminosity (which in fact follows from his 1973 paper), since the later-type galaxies have statistically lower luminosities; it is therefore consistent with the relation determined by Tully and Fisher.

The results described above are so far consistent with the following highly simplified summary; with respect to a photometric radius R_{ph}, R_{max} decreases from late to early types, reflecting the increasing importance of the bulge; within a given type R_{max}/R_{ph} is roughly constant and V_{max} increases with luminosity, reflecting an increase in the total mass. The former is consistent with the traditional interpretation of the morphological sequence, and the latter with the observation that the M/L ratio is roughly the same for all types of galaxies. It is immediately clear that this summary is almost certainly inadequate; however, the available observations are equally inadequate to provide a much more detailed picture. We may see an improvement in the situation in the coming years as the number of optical and high-resolution radio–H I observations of galaxy velocity fields steadily increases.

In this respect the observations have been outrun by the extensive theoretical work of Roberts et al. (1975), who offer an explanation of the two-dimensional classification of spiral galaxies by morphological type and luminosity class in the framework of density wave theory. They conclude that there are two important parameters that are related to the rotation curve and that define the classification: the total mass M_T divided by a characteristic dimension R_c (the corotation radius), and the central mass concentration. The latter parameter (which is perhaps related to the bulge-to-disk ratio) determines the pitch angle of the spiral arms and hence the Hubble type (Sandage 1961). The two parameters together determine in first approximation the strength of the shocks and hence the degree of development of the spiral arms, i.e. the luminosity class (van den Bergh 1960a,b). The model is an ambitious one, and the challenge is out to observers to improve the observational material on which it is presently based; the rotation curves are often derived from only a few long-slit spectra and do not extend very far into the disks, and there is little or no data on the velocity patterns characteristic of density-wave streaming motions which would assist in estimating the corotation radii and provide valuable support for the whole model. Several questions that still need answers are: How does the observed dependence on the total luminosity (or mass) come into the picture? And what determines the corotation radius? These two things are apparently related since the M_T/R_c parameter helps to define the luminosity class. Some support for the model can be found in the correlation of the compression strength with luminosity class that was discovered earlier by van der Kruit (1973c) from radio continuum observations of spiral galaxies. Finally, what is left of the idea that the Hubble type sequence is a sequence of angular momentum per unit mass (e.g. Sandage et al. 1970, but see Nordsieck 1973a,b)? It has been suggested that this latter quantity is related to the compression strength and, in particular, to the origin of the less luminous late-type galaxies[2] (van der Kruit 1973a,b, Wakamatsu 1976).

3.2 *Rotation Curves in the Outer Parts of Spiral Galaxies*

Radio measurements of the H I 21-cm line velocities in galaxies have considerably increased the radial distance to which rotation curves can be obtained; optically derived rotation curves rarely extend beyond $\sim 1/3 R_{\mathrm{Ho}}$, while in H I they often reach beyond R_{Ho}. Before such observations were available it was usually assumed that at large radii the rotation curves eventually became Keplerian, $V_{\mathrm{rot}} \propto R^{-1/2}$. In fact actual rotation curves are now found to decline much more slowly or even not at all (Roberts 1975b, Huchtmeier 1975, Combes et al. 1977). Bosma (1978a,b) has recently analyzed H I velocity fields in a sample of about 20 galaxies,

[2] A source of confusion is the use of de Vaucouleurs' revised types in some studies and of van den Bergh's two-dimensional classification in others. It is evident that there is a great deal of similarity between the two systems, at least for the later types, as reflected in de Vaucouleurs' (1977) luminosity index. On the average, the late revised types are faint luminosity classes: Sc ≈ Sc I, Scd ≈ Sc III, Sm ≈ Sc IV, etc. Many correlations with the later revised types are therefore also correlations with luminosity class.

based on data from new observations with the WSRT and on results available in the literature. His results can be summarized as follows: The rotation curves are almost always either flat or slowly declining in the outer parts.[3] Construction of mass models shows indeed that out to the last observed point the total mass M_{out} still does not converge to an asymptote. The ratio M_{out}/L_{tot} is about 5–15 independent of type ($H_0 = 75\,\text{km sec}^{-1}\,\text{Mpc}^{-1}$) with an indication in a number of galaxies that M_{out}/L_{tot} has a tendency to increase with radius. However, Bosma cautions that, given the uncertainties arising from noncircular motions, beam smoothing, thin disk approximation, etc, these results should be considered as very tentative.

Krumm & Salpeter (1977; see also Salpeter 1978) have extended the H I rotation curves of six mainly edge-on spiral galaxies to even larger distances (84 kpc for NGC 4565 if $H = 50\,\text{km sec}^{-1}\,\text{Mpc}^{-1}$) using the Arecibo radio telescope. They find further evidence that V_{rot} refuses to decrease in the outer parts of these galaxies; however, the very existence of H I there disagrees in two notable cases with observations made with the WSRT (NGC 4565 and 4631, Sancisi 1978) so that these results require further verification.

Rotation curves that remain high at large distances imply increasing M/L ratios in the outer parts of galaxies. Indeed, if the surface brightness continues the exponential decrease found in the brighter parts of the disk (e.g. Freeman 1970a) and the rotation curve remains constant with R, then M_{out}/L_{tot} is proportional to R. Roberts & Whitehurst (1975) derived local M/L values of 200 or more at 30 kpc radius in M31, assuming that the H I velocities that they measured were due to pure rotation and taking a particular model for the mass distribution [see also Roberts (1976)]. Observations of M31 at Cambridge (Emerson & Baldwin 1973) seemed at first to indicate that the rotation curve differed from that derived by Roberts and Whitehurst; however, a more recent analysis (Emerson 1976, Newton & Emerson 1977) has removed the discrepancy. Furthermore, Newton and Emerson conclude that the high degree of (anti-) symmetry of the velocity field on either side of the minor axis of M31 strongly suggests that the observed velocities indeed result from rotation, to better than $10\,\text{km sec}^{-1}$.

Finally, we discuss briefly the question of whether the forms of the rotation curves provide any evidence for massive halos around galaxies.

[3] A notable exception to this general statement is M81 (Rots 1975), where the observed rotation curve on the northwest side begins to increase again beyond about 10 kpc. A convenient excuse for this may be found in a postulated interaction of M81 with M82 and NGC 3077 (see Section 4.6 below). The observed rotation curve on the southeast side continues to decline.

It is certainly true that more mass is waiting to be found beyond the last measured H I points on many rotation curves; the values of a few $\times 10^{11} M_{\odot}$ currently quoted for luminosity class I and II galaxies refer to radii of 20–50 kpc. However, the great increase (factors of 10 to 100) in masses advocated by Einasto et al. (1974) and by Ostriker et al. (1974) involve estimates at much greater radial distances, from 200–500 kpc. As has been stated by Turner & Ostriker (1977), there is no evidence in favour of such massive halos *within* the visible disks of galaxies; the standard rotation curve analyses give values of M_{out} at some R that differ by only $\sim 20\%$ if one assumes a spherical rather than a flattened mass distribution. Nevertheless, it is a fact that not a single galaxy has been found with a Keplerian rotation curve at large R. We must conclude that the results from rotation curves are not inconsistent with the existence of extensive, massive halos around galaxies, although the prime evidence for them comes from studies of binary galaxies and outlying globular clusters (e.g. Turner & Ostriker 1977, Sargent 1977).

3.3 *Velocity Dispersion Measurements*

It is well known that observations of velocity dispersions can provide information on the dynamics of galaxies; for instance, in the central bulges of spiral and elliptical galaxies the velocity dispersion in the stars can be used with the virial theorem to estimate the total masses there, assuming that the kinetic energy is mainly in random motions. We do not review those results here; for recent data see for example Williams (1977) and Illingworth (1977) and references therein. Our concern in this section is with measurements of the Z-component of the velocity dispersion in the gas; in flattened disks this can give information on the thickness of the gas layer or the mass density in the plane. Gottesman & Davies (1970) and de Jager & Davies (1971) found upper limits to the random H I cloud motions of 12 km sec^{-1} in M31 and 10 km sec^{-1} in M33; however, they estimated that the velocity gradients over their telescope beam could seriously affect the interpretation. Using higher angular resolution Emerson (1976) confirmed that the rms dispersion of the H I in M31 is indeed 12 km sec^{-1}. With the help of a mass model determined from the rotation curve, and the assumption of a simple hydrostatic equilibrium in Z (neglecting magnetic fields), he found that the H I layer increases in Z-thickness from about 200 pc around $R = 6$ kpc to 1500 pc at $R = 25$ kpc from the center. From another method, involving analysis of the differential radial velocities along the line of sight, Whitehurst et al. (1978) find a thickness of the H I plane in M31 of about 1.4 kpc between half-density points and large distortion in the outer regions.

There are, of course, necessary assumptions: the measured line-of-sight dispersion is assumed to be a good estimate of the Z-dispersion (note however that M31 is highly inclined), and the mass density is assumed to be constant over the whole Z-extent of the gas layer at every R. This mass density is then derived from the rotation curve with an assumed thickness of the total disk. A similar treatment of M33 provides similar results (Warner et al. 1973): the rms dispersion falls from about 15 km sec^{-1} near the nucleus to 9 km sec^{-1} at 6 kpc, and the H I–layer thickness increases from about 300 pc at 0.5 kpc to 800 pc at 5 kpc radius. Finally, Tully (1974b) has derived information on the thickness of the gaseous disk of M51 from his extensive Hα-line study; the values range from $\sim$60 pc in the central regions to 270 pc out in the main part of the optical disk. The rms velocity dispersions are respectively 30 and 17–20 km sec^{-1} for the two areas. The large thicknesses apply to the giant H II regions where pressure support may play a greater role (see discussion in Tully, 1974b).

A promising future development will be to actually measure the H I–layer thickness from high-resolution radio observations of edge-on galaxies. Along with velocity dispersions obtained from face-on systems, an independent estimate of the mass density near the equatorial plane should then be available which, when coupled with the rotation curve data, would provide some useful constraints on the actual 3-dimensional distribution of mass in disk galaxies.

4 NONCIRCULAR MOTIONS

In all of the velocity fields presently available, one can easily find evidence for deviations from the textbook style of regular, planar circular motion on all length scales ranging right down to the resolution limit of the observations. On the scale of a few hundred parsecs, local erratic motions of 5–10 km sec^{-1} are found everywhere over the disks of spirals and in the irregular galaxies; the viability of the obvious explanations in terms of supernovae explosions or the outflow of matter and radiation from young stars has yet to be examined in detail. In this section we concentrate mainly on deviations at scales of the order of 1 kpc and larger that seem to form systematic patterns over an appreciable part of the disk.

4.1 *The Central Regions*

The necessary angular resolution in the central regions is available only from the optical observations. Motions in or very near to the nuclei of many galaxies have been reviewed by Burbidge (1972) and Ulrich (1974); for a detailed discussion of the central regions of our Galaxy, see Oort (1977).

The gas motions within about 0.4 kpc of the nucleus of M31 show a complex velocity field superposed on rapid rotation (Rubin & Ford 1971), with evidence for expansion at velocities up to 100 km sec^{-1}. Observations of the instellar H and K absorption lines provide further indications of gas ejection from the nucleus with velocities up to 450 km sec^{-1} (Morton & Andereck 1976). The gas motions in the inner 1.5 kpc of M81 are equally complex (Goad 1974, 1976); similar to the situation in M31, the rotation curve rises rapidly to a sharp peak of ~ 300 km sec^{-1} at about 1 kpc, followed by a deep minimum and a second maximum further out in the main part of the disk.[4] Within 300 pc there is an outflow of gas, but just outside this radius the velocity field shows a general inflow towards the center. The nucleus of M81 contains a compact ($\lesssim 6 \times 10^{-3}$ pc = 1300 au) radio continuum source that varies in time (de Bruyn et al. 1976, Kellermann et al. 1976), although it is not particularly intense. The evidence in M31 and M81 seems to indicate a mild case of nuclear activity and gas ejection on a relatively small scale; however, the stars in the disk and the bulge of M31 do not seem to follow the pattern of noncircular motions seen in the gas (Pellet 1976).

Although strong noncircular motions in the central regions of M51 were originally reported by Burbidge & Burbidge (1964), these were not confirmed in the extensive Hα Fabry-Perot observations by Tully (1974a,c), who instead found only small (~ 20 km sec^{-1}) deviations that he suggested were associated with an inner Lindbland resonance. The situation remains ambiguous, however, since de Veny et al. (1976) have recently reconfirmed the earlier reports with new evidence for noncircular motions of up to 75 km sec^{-1}.

The kinematics of the inner rings of bright H II regions found in many galaxies has been investigated in several cases. The ring at ~ 340 pc from the nucleus of the SBb galaxy NGC 3351 is apparently contracting (Rubin et al. 1975). Noncircular motions of the inner ring of H II regions have been observed in NGC 5364 by Goad et al. (1975); a preliminary analysis of the general rotation in that galaxy shows that the H II ring may coincide with the position of the inner Lindblad resonance. A detailed study of the bright inner ring of H II regions in NGC 4736 has been made by van der Kruit (1974a, 1976c). Besides the H II regions themselves, the ring contains diffuse Hα emission with a sharp outer boundary at a radius of about 1 kpc, where a strong decrease in the optical continuum surface brightness and an increase in $(B-V)$ color is also found. In the ring there

[4] The value of 300 km sec^{-1} was derived from spectra near the major axis only. Examination of all Goad's spectra suggests that a significantly lower value of 250–270 km sec^{-1} is a better estimate, illustrating once again that spectra at many position angles are required for an accurate picture.

are two concentrations of nonthermal radio continuum emission (van der Kruit 1971, de Bruyn 1977a) located on roughly opposite sides of the nucleus (itself also a weak radio source) near the places where stubby armlike features seem to emerge from the ring. The H II kinematics studied by van der Kruit shows that expansion motions exist in the ring and that the expansion is strongest at the positions of the radio continuum peaks (but see also Bosma et al. 1977b). Although an explanation in terms of the inner Lindblad resonance would seem attractive (Schommer & Sullivan 1976), the direction of the noncircular motions does not appear to agree with that expected in the linear approximation (van der Kruit 1976c). The possibilities for large-scale organized effects of nuclear activity (see for example Sanders & Bania 1976) or gravitational disturbances remain to be investigated in detail.

Contrasting results are available for the emission-line "hot spots" found near the nuclei of some galaxies. Noncircular motions are possible for such features in NGC 2903 (Simkin 1975b), however, the "hot spots" in the central 2.5 kpc of the "active" galaxy NGC 2782 show a pattern of normal rotation with no noncircular motions in excess of 15 km sec^{-1} along the line of sight (van der Kruit 1977b).

Finally, we mention evidence for substantial noncircular motions in two other cases: Walker's (1968) study of the central region of the Seyfert galaxy NGC 1068 provides detailed evidence for expansion velocities up to 150 km sec^{-1} in the entire area within a radius of 1.5 kpc; Demoulin & Burbidge (1970) and Ulrich (1978) present observations indicating outflow of gas from the nucleus of NGC 253 into a cone-shaped region with velocities reaching 300 km sec^{-1}. The apparent outflow of matter is confirmed by radio measurements of H I absorption against the radio source in the nucleus (Gottesman et al. 1976).

In summary there is good evidence in the velocity patterns of the central regions for noncircular motions and even ejection of the gas on the 1 kpc scale. The explanations are, however, diverse and not always consistent with all the data; in particular the (admittedly sparse) evidence that the stars are not appreciably affected by all the goings-on leaves the suspicion that the peculiar motions in the central regions may not reflect any real asymmetries in the distribution of mass there. More observational material on this latter topic would be very desirable.

4.2 *Large-Scale Effects of Nuclear Activity*

The unusual large-scale morphological and kinematical features that are found in the radio and optical observations of a few galaxies have been interpreted by some authors as the consequence of the expulsion of gas at high speeds from the nuclei. Two classic examples are M82 and NGC 1275 cutoff of $M_v = -5$, respectively, for the β Cephei region, but these conclusions were based on the authors' inability to find new variable stars in a small sample of fainter and brighter candidates. Since the search for new variable stars is still going on (see Section 4.1), and since both fainter and brighter candidates are still being studied, it seems premature to put a numerical value on the high- and low-luminosity ends of the instability strip—Eggen (1975) suggests that it must extend at least from $M_v = -6$ to $M_v = -2$. Nevertheless, it is clear that the β Cephei phenomenon does not persist over an indefinite range of stellar masses, and that therefore the instability strip must be bounded in luminosity and in effective temperature.

Although Watson (1972) found no nonvariable stars within the region occupied by the β Cephei stars in the (θ_e, log g) plane, possibly because the nonvariable stars he observed were too different from the variables in spectral type, Lesh & Aizenman (1973a) concluded that variable and nonvariable stars coexist within the instability strip in the (Q, β) plane. Jones & Shobbrook (1974) determined the mean relation between Q and M_v by the maximum likelihood method, under rather special assumptions concerning the relative size of the errors in these quantities. They concluded that the width of the strip in the (Q, M_v) diagram is not much greater than the expected observational error. However, this does not alter the fact that there exist variables and constant stars having the same effective temperature and luminosity (see also Shaw 1975, Shobbrook 1978).

In the theoretical HR diagram, the β Cephei instability strip coincides remarkably well with the region variously known as the "core collapse zone," "S-bend," or "hydrogen exhaustion phase"—a fact first noted by Schmalberger (1960) and confirmed by every subsequent study of the location of the β Cephei stars in the HR diagram (e.g. Watson 1972, Lesh & Aizenman 1973a, Jones & Shobbrook 1974, Balona & Feast 1975, Shaw 1975, Eggen 1975), despite the fact that different calibration techniques and different theoretical models (with different compositions and opacities) were used by the various authors. This region is traversed three times by a star in the course of its early evolution away from the zero-age main sequence: once in the core hydrogen-burning phase, once in the secondary contraction phase, and once in the shell hydrogen-burning phase. Since no obvious observational parameter—anomalous abundances, multiplicity, rotation, etc—uniquely separates the variable stars from the nonvariable stars within the instability strip, the question arises as to whether the (unobservable) internal structure alone determines which stars are variable and which are not. Following Schmalberger's suggestion that the instability mechanism for β Cephei stars is somehow led to the identification of oval distortions as a common feature of many galaxies.

The structure and dynamics of barred spiral galaxies has been reviewed extensively by de Vaucouleurs & Freeman (1973). There is some evidence for gas streaming in the bars (see also Burbidge 1970), although there are conflicting reports as to whether it flows inward or outward. A case for outward streaming in NGC 4027 was made by de Vaucouleurs et al. (1968); Christiansen & Jefferys (1976) have modelled the velocity field of that galaxy with a high-density prolate spheroid representing the bar embedded off-center in a disk.

Chériguène (1975) presented results from optical emission-line slit spectra along the bars of twelve barred spirals. No obvious noncircular motions were found, although it should be noted that no observations at other slit position angles were made. The results nevertheless suggest that the inferred rotation curve is a function of morphological type in the sense that the total angular velocities in the bar regions decrease from

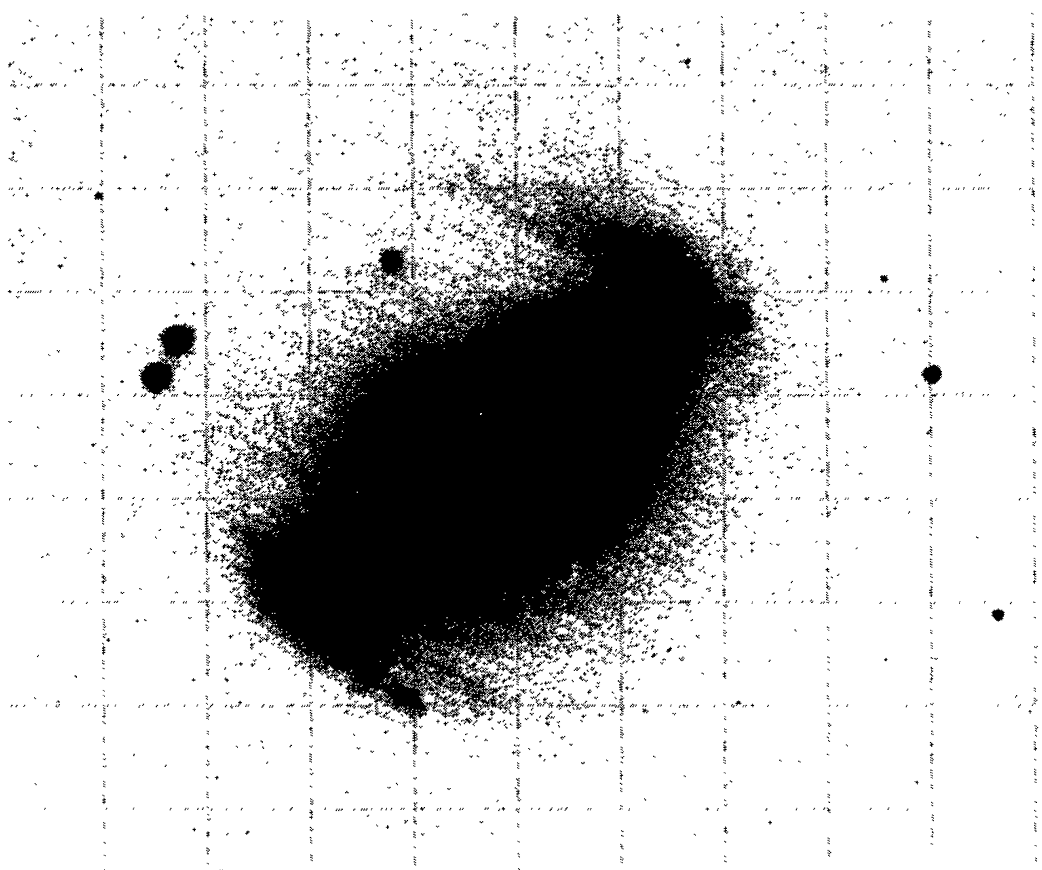
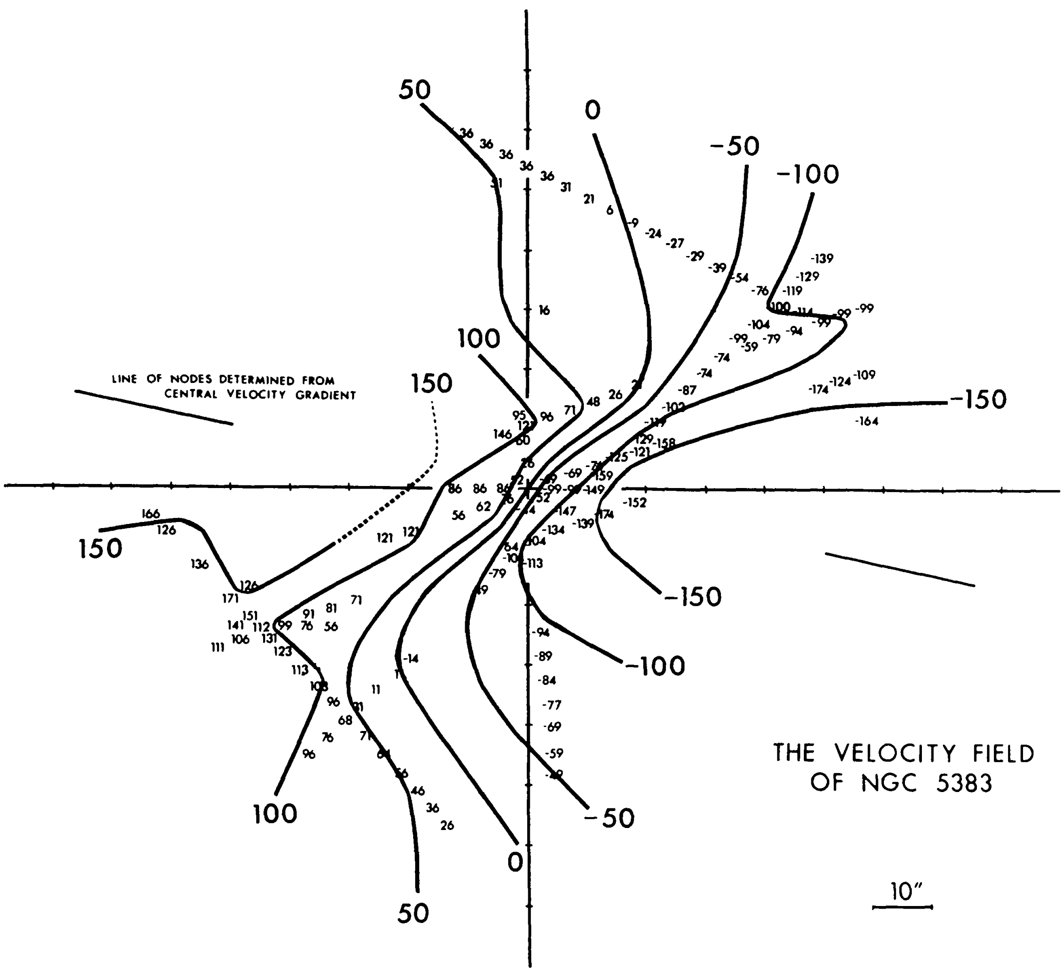


Figure 3 The kinematical effects of bars in galaxies are illustrated for the case of NGC 5383. Above is shown an optical picture of the galaxy and at right the velocity field derived from emission lines on optical slit spectra (Peterson et al. 1978).

$\gtrsim$ 100 km sec^{-1} kpc^{-1} for the SBab, b types to 20–40 km sec^{-1} kpc^{-1} for the SBcd, m. In the IBm galaxies the rotation is very slow. These results are consistent with the single case of measured stellar rotation of 80 km sec^{-1} kpc^{-1} in the bar of the SBb galaxy NGC 3351 (Peterson et al. 1976).

The most extensive observations presently available on a barred spiral galaxy are those for NGC 5383 (Figure 3). The velocity field obtained from radio–H I data provide evidence for an underlying massive disk in normal differential rotation, upon which disturbances of the order of 50 km sec^{-1} are superposed in the region of the bar (Allen et al. 1973a, Sancisi 1975). Optical measurements of the emission-line velocity field (Peterson et al. 1978, Duval 1977) confirm the presence of velocity perturbations in the bar and can be interpreted as inward-streaming motions of up to 180 km sec^{-1} along the bar (Peterson et al. 1978). More complicated streaming patterns associated with shocks in the gas are expected on the basis of hydrodynamical calculations (Huntley et al. 1978,



and references therein), and a comparison with the observations should prove rewarding.

The presence of an underlying massive disk has been discovered also in NGC 3359 by Siefert et al. (1975), and evidence for noncircular motions near the bar of NGC 660 has been presented by Benvenuti et al. (1976).

We turn now to the evidence for the presence of oval distortions in galaxies which, at least from the appearance of their optical images, were not formerly suspected of having them (but see Freeman 1970b). The H I observations of NGC 4151 and NGC 4736 (Bosma et al. 1977a,b) show a large-scale feature in their velocity fields (see Figure 4): The apparent

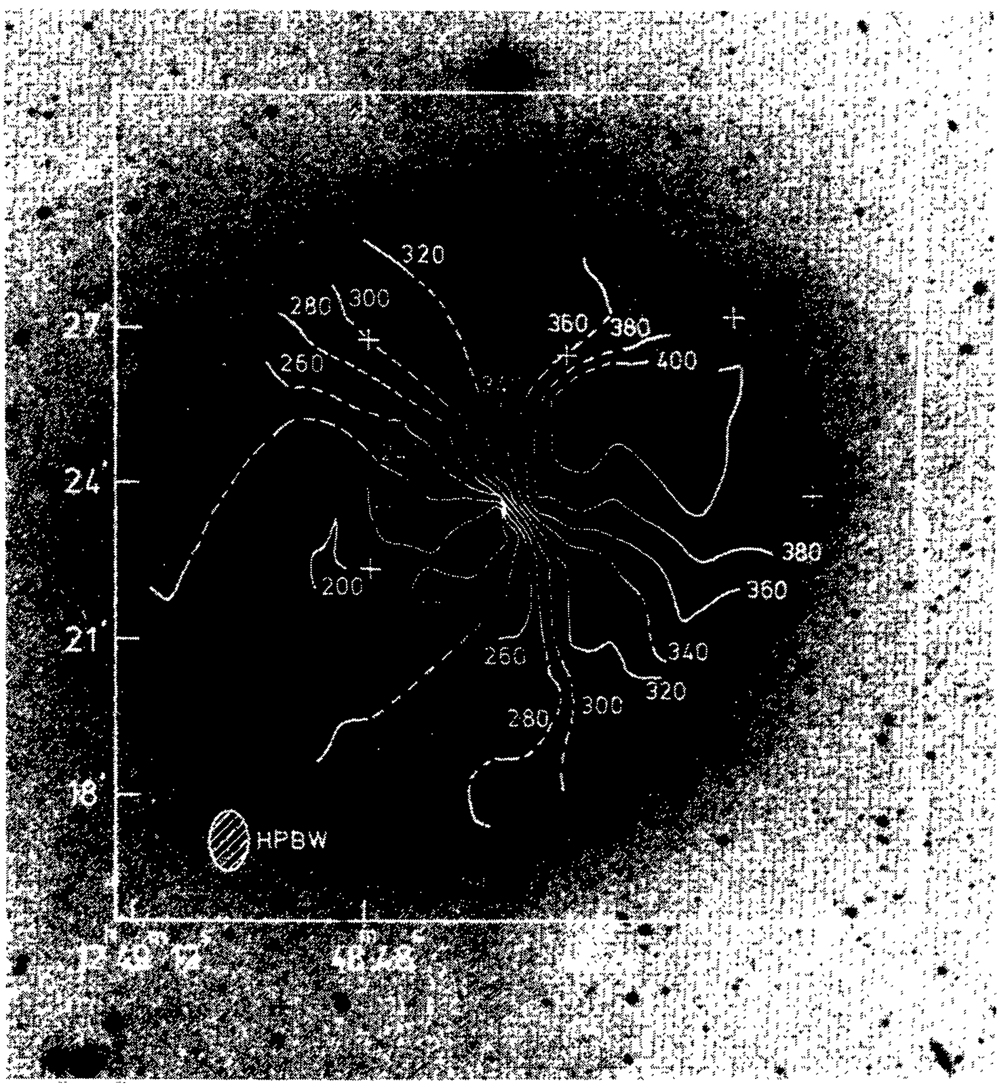


Figure 4 The kinematical effects of an oval distortion in the inner disk are evident in the radial velocity field of the H I in NGC 4736 (Bosma et al. 1977b). The kinematical "line-of-nodes" has an S-shape, which in the inner region is inconsistent with the major axis of the optical isophotes. Note that H I is detected in the faint outer ring.

dynamical "major axis" in fact has an S shape, and in the inner regions the position angle is inconsistent with that of the optical isophotes. The interpretation offered is that the potential distribution in the central area is an oval-shaped disk or a "fat bar." A qualitative model for NGC 4736 is able to describe both the velocity perturbations and the distribution of light, including the faint outer ring (Bosma et al. 1977b). The line of nodes found from the H I observations in the far outer parts of NGC 4151 (Davies 1973, Bosma et al. 1977a) indicates that the velocities observed optically near the center are mainly rotational (Anderson 1974, Fricke & Reinhardt 1974), although there is still evidence for noncircular motions of the H II regions near the ends of the "fat bar" (Simkin 1975b).

4.4 *Density Wave Streaming*

One of the major motivations for making extensive high-resolution radio–H I observations of velocity fields in spiral galaxies has been to search for the characteristic streaming motions of the gas caused by an underlying density wave in the stellar disk. The resolution requirements are severe for radio telescopes (Allen 1975a), and results are available for only a few nearby galaxies.

Much attention has of course been paid to M31, although its relatively high inclination makes the interpretation difficult. This is especially so along the minor axis where the radial component of the streaming is otherwise best observed. Guibert (1974) showed that the spiral pattern is at least consistent with the rotation curve and linear density-wave theory. The velocity field was studied in greater detail by Emerson (1976), who found peculiar motions of $\sim 30\ \text{km sec}^{-1}$ associated with the arms; on the major axis the motions are consistent with theory, but on the minor axis they appear to have the wrong sign. Another interpretation that is offered by Emerson for the motions near the major axis involves simply the self-gravitational effects of the H I gas in the arms. To complicate affairs, the WSRT observations (Shane 1978) have indicated that two arms around the near minor axis of M31 at 5 and 9 kpc from the center are apparently contracting and expanding with respectively 30 and 20 km sec^{-1}.

In M33 Warner et al. (1973) could find no evidence for density-wave systematic motions in the disk with amplitudes larger than $3\ \text{km sec}^{-1}$. On the other hand, Rogstad et al. (1974) do find some evidence for a weak density-wave streaming of about $4\ \text{km sec}^{-1}$ with corotation at ~ 2.4 kpc.

A pattern of density-wave motions with velocities of $\sim 20\ \text{km sec}^{-1}$ was found in M101 by Rogstad (1971) from radio–H I observations with an angular resolution of 4′. Later measurements at a resolution of about 0′.5 (Allen 1975a) revealed that the H I is indeed concentrated in ridges on the optically visible arms, but there is little evidence for the interpretation in terms of streaming velocities as reported earlier. The different results serve to illustrate the serious effects of confusion of spiral arms in low-resolution observations, and confirm the need for a minimum resolution in terms of the arms spacing. Note that, owing to the low inclination of the galaxy, streaming motions of 15 km sec^{-1} in the plane are not yet excluded by the observations.

Segalovitz (1976) has constructed a nonlinear density-wave model for M51; however, after smoothing the model to the resolution of the radio–H I observations, the amplitude of the streaming motions becomes too small for a conclusive test. Tully (1974c) finds evidence for density-wave streaming in the Hα velocity map of M51 that is consistent with the linear theory.

The most convincing evidence for the existence of density-wave motions is to be found in the radio–H I map of the velocity field of M81. From measurements at 0$'$.5, Rots (1975) showed that there are indeed systematic motions in the spiral arms of M81 that are reasonably consistent with linear density-wave theory. An extensive and detailed analysis of the observations has been made by Visser (1975, 1978a,b): The spiral pattern of the underlying stellar density wave is computed with the linear theory, using the optical surface photometry by Schweizer (1976) to determine the wave amplitude; the flow pattern and density distribution of the H I is then calculated using nonlinear gas dynamics. The models are finally smoothed to the angular resolution of the observations for comparison (see Figure 5). From this it follows that the kinematical effects of the shock are visible when the resolution is about $\frac{1}{6}$ of the arm spacing, while the systematic streaming motions can still be clearly detected with a resolution of $\frac{1}{3}$ of the arm spacing. For beamwidths greater than about $\frac{2}{3}$ of the arm spacing, density-wave effects are no longer discernable. A convincing picture emerges, with strict constraints on the parameters of the model. The results for M81 must be considered as strong evidence for the existence of density waves, and as supporting a description of these waves based on the WKBJ analysis of Lin & Shu (1964, 1966) and Roberts (1969). The question of the origin and maintenance of the density wave in M81 has not yet been investigated in the same detail; in this respect it is perhaps not entirely coincidental that the available observations of the area around M81 point to interactions with both M82 and NGC 3077 (Cottrell 1977, van der Hulst 1977).

It is unfortunate that other galaxies that are similar to M81 in optical appearance are beyond the resolution capabilities of present day radio telescopes, at least as far as further detailed tests of the density-wave theory are concerned.

We mention finally one other case where systematic streaming velocities have been found. The optically observed velocity field in the central areas of the peculiar galaxy NGC 3310 shows strong noncircular motions associated with the spiral arms (van der Kruit 1976a, Figure 6). If these

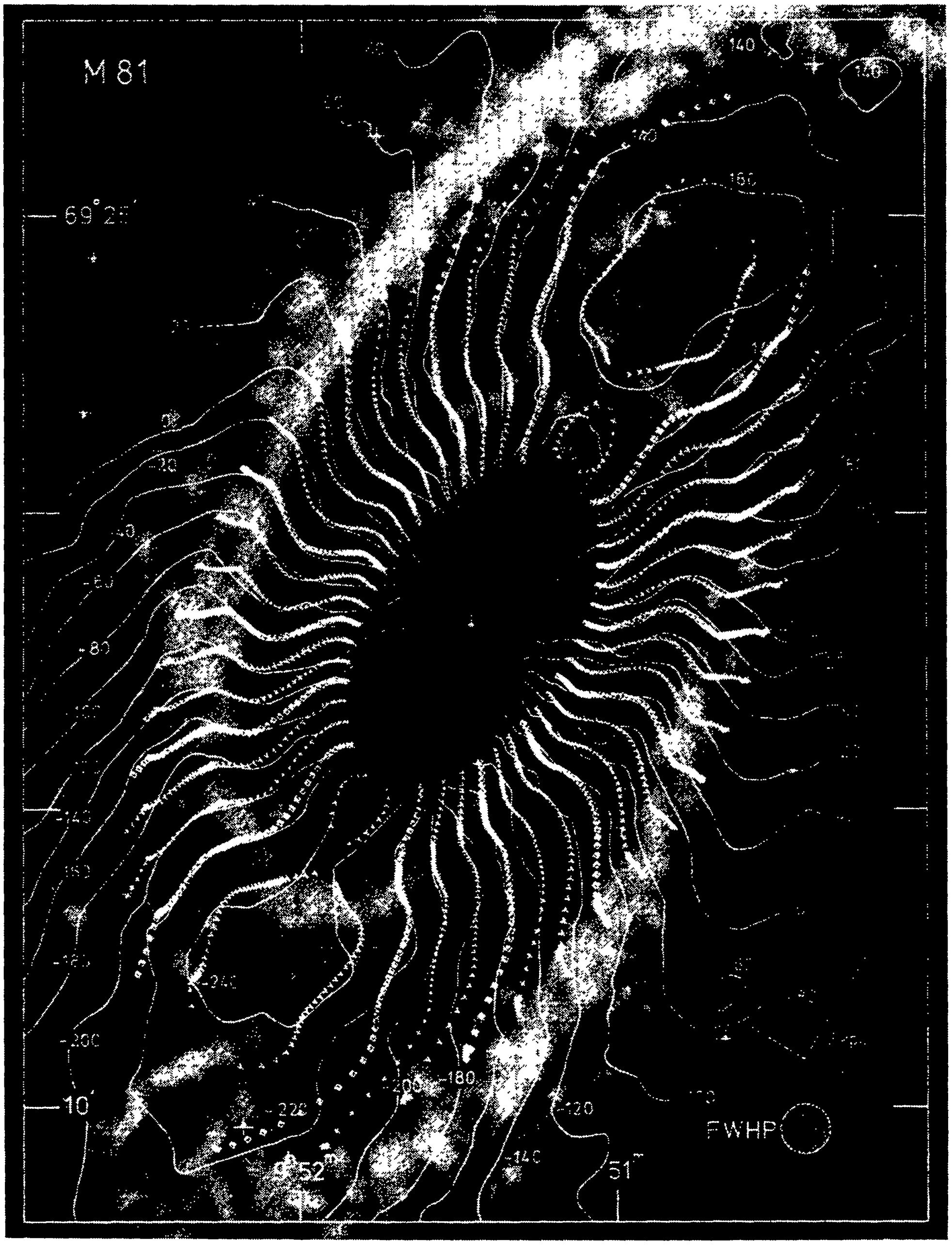


Figure 5 Comparison of the observed velocity field in the H I of M81 with the predictions of a self-consistent density wave model (Visser 1978a, b). The underlying intensity distribution is the observed H I surface density distribution at a resolution of 25″. The full-drawn lines are observed contours of radial velocity after smoothing of the original data to a beam of 50″ (indicated at lower-right). The dashed lines are the predicted velocities in the density-wave model also smoothed to the resolution of 50″.

velocities are ascribed to density waves, the amplitude of the streaming is $\frac{1}{3}$ to $\frac{1}{2}$ of the rotational speed. A number of other properties of this galaxy are at least qualitatively consistent with strong compression in the spiral arms: ridges of radio continuum emission, intense Hα emission, blue colors, and UV excess (van der Kruit & de Bruyn 1976). The inference from this and from the low M/L ratio is that the galaxy has experienced a recent ($\sim 10^7$ years ago) burst of star formation that may have been caused by the excitation of an unusually strong density wave.

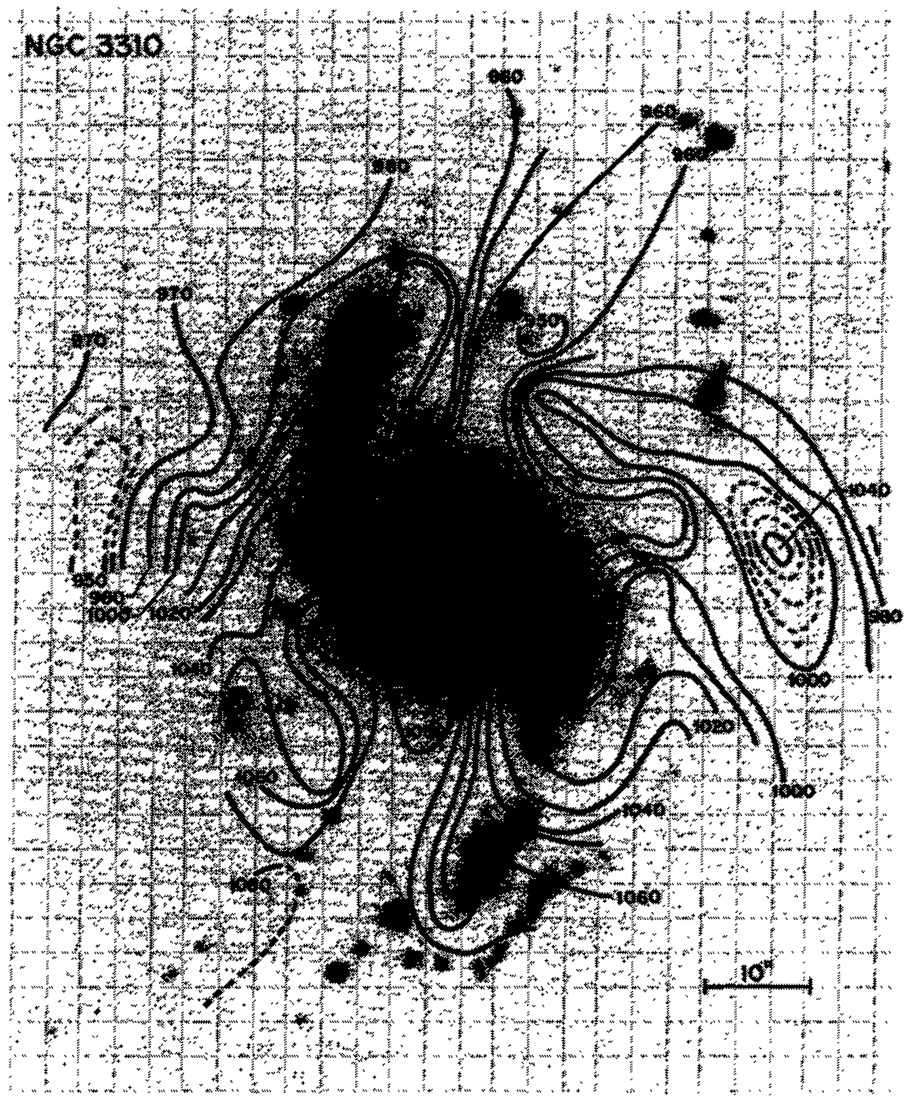


Figure 6 Severe effects of noncircular motions associated with the spiral structure are observed in NGC 3310 (van der Kruit 1976a). The velocity field shown here is constructed from measurements on emission lines in a large set of optical spectra. In spite of the large noncircular motions, which are probably effects of unusually strong density-wave streamings, the basic rotation pattern is still visible. The orientation of NGC 3310 is that used for the schematic illustration in Figure 1.

4.5 *Warps in the Outer Parts of Spiral Galaxies*

It has been known for some time that the H I layer in the outer parts of our Galaxy ($R \gtrsim 12$ kpc) is warped to large distances ($Z \lesssim 2$ kpc) from the plane defined by the inner regions (see e.g. Verschuur 1975 and references therein). A tidal interaction model involving a close passage of the LMC has been proposed by Hunter & Toomre (1969), but the situation has become more complicated since the discovery of the Magellanic Stream (Mathewson et al. 1974).

From single-dish measurements Roberts & Whitehurst (1975) showed that the H I in the outer southern parts of M31 is also warped to distances of 5 kpc out of the conventionally defined plane. Radio-synthesis techniques are less sensitive to the extended galactic H I, which confuses the single-dish observations in the northern part of M31, and the recent synthesis observations by Newton & Emerson (1977) have confirmed the existence of a warp there in the opposite direction to that found on the southern side of the galaxy. They have also fitted a model to the H I distribution and velocity field involving concentric annular rings that are progressively more inclined at larger radial distances, in the manner first proposed for M83 by Rogstad et al. (1974, see below). The maximum deviation from the centrally defined plane is 6 kpc at about 30 kpc from from the center. Roberts and Whitehurst concluded that in their model for the bend noncircular motions associated with the deviations are likely to be so small that they do not seriously affect the rotation curve determined from conventional methods even in the warp region. However, changes in the rotation velocity of only 10 km sec^{-1} can result in drastic changes in the inferred M/L ratio (Baldwin 1975).

Lewis (1968) noted that the velocity field in the relatively extensive H I distribution of M83 indicates a change of the apparent major axis with radius. The H I–synthesis observations of Rogstad et al. (1974) confirmed this feature in the velocities (Figure 7), and these authors proposed a detailed model for the kinematics: The H I distribution is represented by annular rings in circular motion, progressively more inclined at larger radii. With a reasonable choice of the viewing geometry, their model could also represent bright ridges found in the H I surface-density distribution in the outer parts of the galaxy as effects of longer path lengths through the highly inclined annuli. Rogstad et al. also noted an important dynamical property of the inclined rings: owing to the torque exerted by the inner part of the galaxy, the rings are expected to slowly precess. This implies an age of no more than about 2×10^9 years for the disturbance. A similar model with rather severe warping has been proposed for M33 by Rogstad et al. (1976) as a method of explaining the wing-like features to the north and south of the galaxy and the occurrence of double profiles in certain parts of the disk.

The feature of a changing kinematical major axis with increasing radius has been noted for several other galaxies by Bosma (1978a,b). He suggests that the effects are distinguishable from oval distortions in that the major axis agrees with that of the optical image in the inner parts of the galaxy (compare Figures 4 and 7).

A more direct way to look for warps is to study edge-on galaxies. Sancisi (1976) has found warps in the H I distributions of four out of five systems observed (NGC 5907, 4565, 4244, and 4631); the only exception is NGC 891 (Sancisi et al. 1974).

What evidence is there that the warps found in the H I data have counterparts in the stellar disks? The photometry of NGC 4565 (see H.

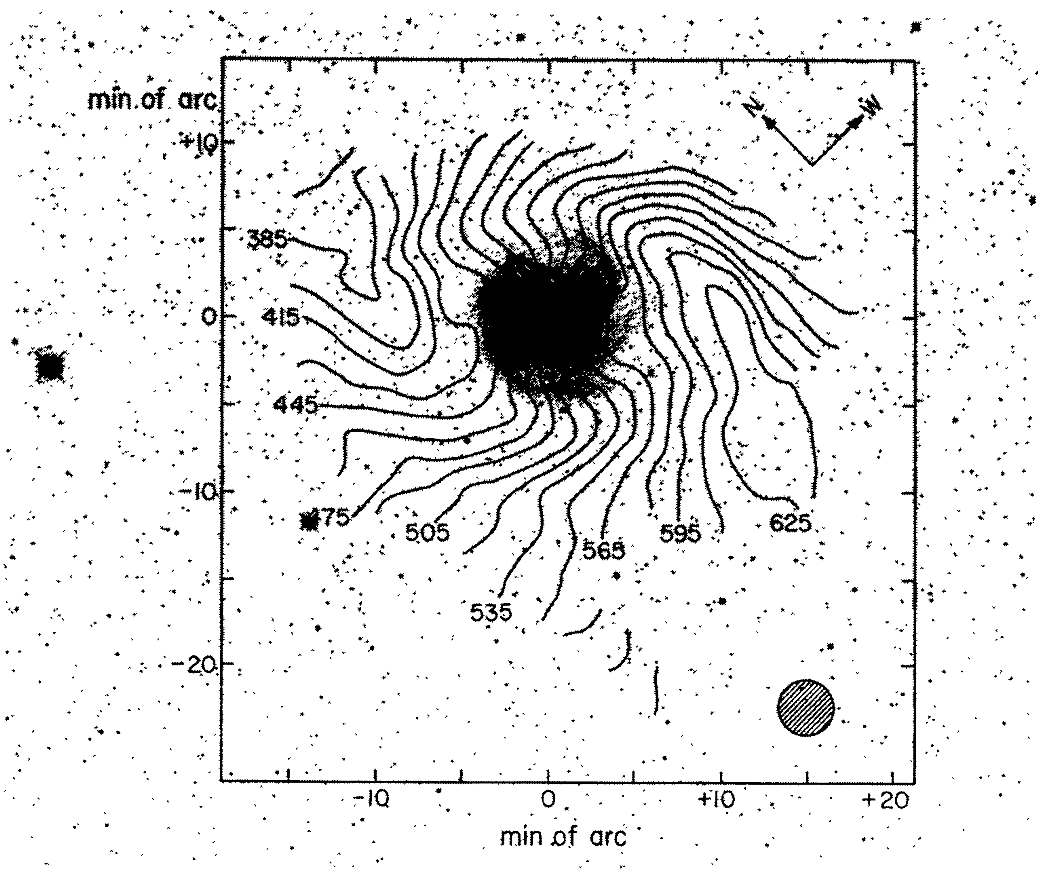


Figure 7 The velocity field of M83 derived from H I aperture synthesis observations shows a strong variation of the position angle of the kinematical major axis with distance from the center. The underlying optical picture from the Palomar Sky Survey shows that the horizontal axis of the figure corresponds approximately to the major axis of the optical image of the galaxy. The distortions in the velocity field are interpreted as a result of a severe warping of the outer parts of the plane of the galaxy (Rogstad et al. 1974).

Spinrad's results in Frankston & Schild 1976, Bertola & di Tullio 1976) shows some indication of a warp in the far outer parts of the optical image in a way consistent with the even more distant H I warp, but the evidence is not very clear. Features found in the outer parts away from the centrally defined planes of NGC 5907 and NGC 4244 could simply be isolated bright clusters of stars and H II regions. We must conclude that the optical counterparts to the H I warps have not yet been convincingly identified. In this respect it is perhaps useful to note that the H I warps in the edge-on galaxies mentioned above do not develop gradually at ever-increasing radial distances, but instead appear abruptly at the edge of the optical disks as seen on standard photographs (e.g. Palomar Sky Survey).

The origin of these warps is not yet clear. The tidal interaction picture of Hunter and Toomre is surely an obvious one to try; however, several difficulties remain in the models of M83 and M33, perhaps the main one being the relatively short time scale (of the order of 10^9 yrs) for disruption of the warp due to differential precession of the rings. A more devastating counter-argument is the simple observation that more than half of the galaxies with evidence for H I warps in the presently available sample do not have any obvious nearby neighbours with which to interact in the time scale available. An explanation of the warps seen in the edge-on galaxies in terms of very distant spiral arms coupled with a slight tilt of the plane with respect to the line of sight (Byrd 1977) is probably inconsistent with the observed H I velocities. Interaction with an intergalactic wind (Kahn & Woltjer 1959) or gas cloud (Sancisi 1976) remains a possibility.

Finally, with respect to the suggestion that the *inner* parts of NGC 5383 are warped (Peterson et al. 1978) we make the following remark: the H I evidence for an extensive underlying disk in this galaxy (Allen et al. 1973a) and its optical structure (van der Kruit & Bosma 1978a) indicate that the optical velocity field of Peterson et al. in the region of the bar should probably be interpreted instead as streaming of the gas along the bar.

4.6 *Kinematical Effects of Tidal Interactions*

We close this travelogue of disk-galaxy kinematics from the nuclei to the peripheries with a brief summary of the results on tidally interacting systems. In contrast to the case of warps discussed above, there is here no doubt that more than one galaxy is involved. Toomre & Toomre (1972) have been very successful in representing the geometry of four examples with models of gravitationally induced tidal disturbances that result in the formation of bridges and tails. The kinematical predictions of these models have been largely confirmed by spectroscopic observations of Arp 295 (Stockton 1974b), NGC 4676 (Stockton 1974a), and NGC 5195 (Schweizer

1977). The existence of H I in the optical tails of NGC 4038/39 was first reported by Huchtmeier & Bohnenstengel (1975), and a detailed study of the H I kinematics has been recently completed by van der Hulst (1977, 1978). In this last example the observations are in very good agreement with the model when a reasonable adjustment of the parameters is made.

The M81 group has also been examined in detail. Roberts (1972) and Davies (1974) were the first to show that H I is distributed extensively between the triplet of galaxies M81, M82, and NGC 3077. Cottrell (1976a) found the H I in NGC 3077 to be strongly distorted and displaced about 4 kpc from the optical center; a computer simulation showed that this could be the result of a close encounter with M81 about 2 to 6 $\times$ 10^8 years ago. In a more sensitive survey of the area between M81 and NGC 3077, van der Hulst (1977, 1978) discovered a bridge of H I containing narrow filaments ($\lesssim$3 kpc wide) which seems to extend from the outermost western arm of M81 around to the south and then eastward to join NGC 3077, 45 kpc away. The shape and kinematics of this bridge could be approximately represented by a simplified computer model of tidal interactions between the members of the triplet a few times 10^8 years ago. Van der Hulst also pointed out the similarity of the M81–NGC 3077 bridge to the Magellanic Stream in the Local Group (Mathewson et al. 1974).

M81 and M82 also appear to be joined by a clumpy bridge of H I (Rots 1975, Gottesman & Weliachew 1977). This feature was mapped in more detail by Cottrell (1977), who proposed a gravitational interaction model where M81 and M82 would have had a very close ($\sim$9 kpc) encounter about 2 $\times$ 10^8 years ago. Some of the curious morphological and kinematical features of M82 and the velocity disturbances of the outer northern part of M81 may also find an explanation in this encounter model.

The H I bridge and spurs found in the NGC 4631–NGC 4656 system (Roberts 1968, Weliachew 1969, Winter 1975, Weliachew et al. 1978) have been modelled with reasonable success by Combes (1978).

The distorted H I distribution and velocity field in the outer parts of M101 (Beale & Davies 1969, Allen 1975a) may also be caused by gravitational interaction, although a detailed model has yet to be presented.

Byrd (1976) has constructed a model to represent local small disturbances in the velocity field of M31 as the result of a passage of M32 right through the disk of M31. The model does not result in the formation of a large-scale warp of the sort described in Section 4.5 above. The absence of measurable H I in M32 ($M_{HI} < 1.5 \times 10^6 M_\odot$; Emerson, 1974) presents some difficulty here, in view of the observed features in the M81–NGC 3077 system.

5 CONCLUDING REMARKS

The ever-increasing refinement of observing methods has clearly produced a wealth of new and detailed kinematical information on disk galaxies in the last few years. A number of general features are appearing, superposed on the major pattern of circular rotation: large-scale disturbances in the inner regions are possibly associated with bars and oval distortions or with nuclear explosions; warping of the disks in the outer parts is not uncommon; the flatness of rotation curves at large radial distances has important consequences for models of the mass distribution.

The translation of these results into statements on the internal dynamics of galaxies is, however, not always clear. The goal of discovering the physical basis for the morphological classification schemes remains a distant one, apparently confused by a number of effects that disturb the pattern of central symmetry so common to the models. Indeed, when studied in detail each and every galaxy has unique properties that would seem to defy generalization; and yet no one can deny the ability of the various morphological classification schemes to put the great majority of galaxies into ordered sequences.

Although more detailed dynamical models of particular well-observed galaxies can obviously be made and would be of great value, it seems to us that the picture may also become clearer by taking a somewhat less-detailed look at a larger sample of galaxies covering a range of morphological types and luminosities. It would surely have been difficult to arrive for example at the Hubble sequence (e.g. Hubble 1926) with a sample of scarcely more than twenty or thirty galaxies, the number discussed in this review.

We can therefore make the safe, canonical statement that more data are needed. Experience shows that combined observations at radio and optical wavelengths on the same objects are particularly fruitful. In the future these measurements should be aimed at obtaining an ever increasing body of homogeneous observational data to provide information on the radial distributions of properties such as the optical and radio continuum emission, gaseous and total mass densities, and colors and abundances. After all, "The nature of the universe may eventually be rationalized by theoretical understanding, but it will not be discovered in the first place by pure thought" (King 1975).

ACKNOWLEDGMENTS

We are pleased to thank several of our colleagues in Groningen for their comments, and especially G. S. Shostak for a critical reading of an earlier version of this paper. We thank Mrs. R. Olde for her work on the manuscript. We are grateful to Drs. A. Bosma, J. M. van der Hulst, D. H. Rogstad, V. C. Rubin, and H. C. D. Visser for permission to reproduce their figures.

Literature Cited

Albada, G. D. van, Shane, W. W. 1975. *Astron. Astrophys.* 42:433

Allen, R. J. 1975a. *La Dynamique des Galaxies Spirales*, ed. L. Weliachew, p. 157. Paris: C.N.R.S.

Allen, R. J. 1975b. See Allen 1975a, p. 285

Allen, R. J. 1976. *Sky and Telesc.* 52:334

Allen, R. J., Goss, W. M., Sancisi, R., Sullivan, W. T. III, Woerden, H. van. 1973a. *I.A.U. Symp. 58, The Formation and Dynamics of Galaxies*, ed. J. R. Shakeshaft, p. 425. Dordrecht: Reidel

Allen, R. J., Goss, W. M., Woerden, H. van. 1973b. *Astron. Astrophys.* 29:447

Allen, R. J., Hamaker, J. P., Wellington, K. J. 1974. *Astron. Astrophys.* 31:71

Anderson, K. S. 1974. *Ap. J.* 189:195

Andrews, P. J., Evans, T. L. 1972. *MNRAS* 159:445

Argyle, E. 1965. *Ap. J.* 141:750

Babcock, H. W. 1939. *Lick. Obs. Bull.* 19:41

Baldwin, J. E. 1975. *I.A.U. Symp. 69, Dynamics of Stellar Systems*, ed. A. Hayli, p. 341. Dordrecht: Reidel

Baldwin, J. E. 1976. *R. Greenwich Obs. Bull.* No. 182, p. 207

Baldwin, J. E., Field, C., Warner, P. J., Wright, M. C. H. 1971. *MNRAS* 154:445

Beale, J. S., Davies, R. D. 1969. *Nature* 221:531

Benvenuti, P., Capaccioli, M., d'Odorico, S. 1976. *Astron. Astrophys.* 53:141

Bergh, S. van den. 1960a. *Ap. J.* 131:215

Bergh, S. van den. 1960b. *Ap. J.* 131:558

Bergh, S. van den. 1976. *Ap. J.* 206:883

Bertola, F., Tullio, G. di. 1976. *Stars and Galaxies from Observational Points of View*, ed. E. K. Kharadze, p. 423. Abastumani Astrophys. Obs.

Bosma, A. 1978a. *I.A.U. Symp. 77, Structure and Properties of Nearby Galaxies*, ed. E. M. Berkhuijsen, R. Wielebinski, Discuss. I. 3. Dordrecht: Reidel. In press

Bosma, A. 1978b. PhD thesis. Univ. Groningen, The Netherlands

Bosma, A., Ekers, R. D., Lequeux, J. 1977a. *Astron. Astrophys.* 57:97

Bosma, A., Hulst, J. M. van der, Sullivan, W. T. III. 1977b. *Astron. Astrophys.* 57:373

Boulesteix, J., Courtès, G., Laval, A., Monnet, G., Petit, H. 1974. *Astron. Astrophys.* 37:33

Boulesteix, J., Dubout-Crillon, R., Monnet, G. 1970. *Astron. Astrophys.* 8:204

Boulesteix, J., Monnet, G. 1970. *Astron. Astrophys.* 9:350

Brosche, P. 1971. *Astron. Astrophys.* 13:293

Brosche, P. 1973. *Astron. Astrophys.* 23:259

Bruyn, A. G. de. 1977a. *Astron. Astrophys.* 54:491

Bruyn, A. G. de. 1977b. *Astron. Astrophys.* 58:221

Bruyn, A. G. de, Crane, P. C., Price, R. M., Carlson, J. B. 1976. *Astron. Astrophys.* 46:243

Burbidge, E. M. 1962. *I.A.U. Symp. 15, Problems of Extragalactic Research*, ed. G. C. McVittie, p. 85. New York: Macmillan

Burbidge, E. M. 1970. *Comments Astrophys. Space Phys.* 2:25

Burbidge, E. M., Burbidge, G. R. 1964. *Ap. J.* 140:1445

Burbidge, E. M., Burbidge, G. R. 1975. *Stars and Stellar Systems IX: Galaxies and the Universe*, ed. A. Sandage, M. Sandage, J. Kristian, p. 81. Univ. of Chicago Press

Burbidge, G. R. 1972. *Ann. Rev. Astron. Astrophys.* 10:369

Burbidge, G. R., Burbidge, E. M., Sandage, A. R. 1963. *Rev. Mod. Phys.* 35:947

Burns, W. B., Roberts, M. S. 1971. *Ap. J.* 166:265

Byrd, G. G. 1976. *Ap. J.* 208:688

Byrd, G. G. 1977. *Bull. Am. Sstron. Soc.* 9:364

Carozzi, N. 1977. *Astron. Astrophys.* 55:261

Carranza, G., Courtès, G., Georgelin, Y., Monnet, G., Pourcelot, A. 1968. *Ann. Astrophys.* 31:63

Carranza, G., Crillon, R., Monnet, G. 1969. *Astron. Astrophys.* 1:479

Carranza, G., Monnet, G., Chériguène, M. F. 1971. *Astron. Astrophys.* 10:467

Chériguène, M. F. 1975. See Allen 1975a, p. 439

Chériguène, M. F., Monnet, G. 1972. *Astron. Astrophys.* 16:28

Christiansen, J. H., Jefferys, W. H. 1976. *Ap. J.* 205:52

Combes, F. 1978. See Bosma 1978a, Discuss. V. 3

Combes, F., Gottesman, S. T., Weliachew, L. 1977. *Astron. Astrophys.* 59:181

Cottrell, G. A. 1976a. *MNRAS* 174:455

Cottrell, G. A. 1976b. *MNRAS* 177:463

Cottrell, G. A. 1977. *MNRAS* 178:577

Courtès, G. 1960. *Ann. Astrophys.* 23:115
Courtès, G. 1964. *Astron. J.* 69:325
Courtès, G. 1972. *C. R. Acad. Sci. Paris Ser.* B. 275:759
Crillon, R., Monnet, G. 1969a. *Astron. Astrophys.* 1:449
Crillon, R., Monnet, G. 1969b. *Astron. Astrophys.* 2:1
Danziger, I. J., Chromey, F. R. 1972. *Astrophys. Lett.* 10:99
Davies, R. D. 1972. *I.A.U. Symp. 44, External Galaxies and Quasi-Stellar Sources*, ed. D. S. Evans, p. 67. Dordrecht: Reidel
Davies, R. D. 1973. *MNRAS* 161:25P
Davies, R. D. 1974. See Allen et al. 1973a, p. 119
Davies, R. D., Gottesman, S. T. 1970. *MNRAS* 149:237
Deharveng, J. M. 1971. PhD thesis, Univ. of Marseille, France
Deharveng, J. M., Pellet, A. 1970. *Astron. Astrophys.* 7:210
Deharveng, J. M., Pellet, A. 1975a. *Astron. Astrophys.* 38:15
Deharveng, J. M., Pellet, A. 1975b. *Astron. Astrophys. Suppl.* 19:351
Demoulin, M.-H., Burbidge, E. M. 1970. *Ap. J.* 159:799
Demoulin, M.-H., Tung Chan, Y. W. 1969. *Ap. J.* 156:501
Dubois, P. 1975. *Astron. Astrophys.* 40:227
Duval, M. F. 1977. *Astrophys. Space Sci.* 48:103
Einasto, J., Kaasik, A., Saar, E. 1974. *Nature* 250:309
Emerson, D. T. 1974. *MNRAS* 169:607
Emerson, D. T. 1976. *MNRAS* 176:321
Emerson, D. T., Baldwin, J. E. 1973. *MNRAS* 165:9P
Erkes, J. W., Turner, K. C., Connors, D. T. 1973. *Bull. Am. Astron. Soc.* 5:430
Faber, S. M., Balick, B., Gallagher, J. S., Knapp, G. R. 1977. *Ap. J.* 214:383
Feast, M. W. 1970. *MNRAS* 149:291
Frankston, M., Schild, R. 1976. *Astron. J.* 81:500
Freeman, K. C. 1970a. *Ap. J.* 160:811
Freeman, K. C. 1970b. *I.A.U. Symp. 38, The Spiral Structure of Our Galaxy*, ed. W. Becker, G. Contopoulos, p. 351. Dordrecht: Reidel
Freeman, K. C. 1975. See Burbidge & Burbidge 1975, p. 409
Fricke, K. J., Reinhardt, M. 1974. *Astron. Astrophys.* 37:349
Georgelin, Y., Monnet, G. 1970. *Astrophys. Lett.* 5:213
Goad, J. W. 1974. *Ap. J.* 192:311
Goad, J. W. 1976. *Ap. J. Suppl.* 32:89
Goad, J. W., Strom, S. E., Goad, L. E. 1975. *Bull. Am. Astron. Soc.* 7:395
Gordon, K. J. 1971. *Ap. J.* 169:235
Gottesman, S. T., Davies, R. D. 1970. *MNRAS* 149:263
Gottesman, S. T., Lucas, R., Weliachew, L., Wright, M. C. H. 1976. *Ap. J.* 204:699
Gottesman, S. T., Weliachew, L. 1975. *Ap. J.* 195:23
Gottesman, S. T., Weliachew, L. 1977. *Ap. J.* 211:47
Guibert, J. 1973. *Astron. Astrophys. Suppl.* 12:263
Guibert, J. 1974. *Astron. Astrophys.* 30:353
Hodge, P. W. 1974a. *Publ. Astron. Soc. Pac.* 86:845
Hodge, P. W. 1974b. *Ap. J.* 191:L21
Hindman, J. V. 1967. *Aust. J. Phys.* 20:147
Hubble, E. 1926. *Ap. J.* 64:321
Huchtmeier, W. 1973. *Astron. Astrophys.* 22:91
Huchtmeier, W. 1975. *Astron. Astrophys.* 45:259
Huchtmeier, W., Bohnenstengel, H.-D. 1975. *Astron. Astrophys.* 41:477
Hulst, H. C. van de, Raimond, E., Woerden, H. van. 1957. *Bull. Astron. Inst. Neth.* 14:1
Hulst, J. M. van der. 1977. PhD thesis, Univ. of Groningen, The Netherlands
Hulst, J. M. van der. 1978. See Bosma 1978a, Pap. V. 2
Huntley, J. M., Sanders, R. H., Roberts, W. W. 1978. *Ap. J.* 221:521
Hunter, C., Toomre, A. 1969. *Ap. J.* 155:747
Illingworth, G. 1977. *Ap. J.* 218:L43
Israel, F. P., Goss, W. M., Allen, R. J. 1975. *Astron. Astrophys.* 40:421
Israel, F. P., Kruit, P. C. van der. 1974. *Astron. Astrophys.* 32:363
Jager, G. de, Davies, R. D. 1971. *MNRAS* 153:9
Kahn, F. D., Woltjer, L. 1959. *Ap. J.* 130:705
Kellerman, K. I., Shaffer, D. B., Pauliny-Toth, I. I. K., Witzel, A. 1976. *Ap. J.* 210:L121
King, I. R. 1975. See Baldwin 1975, p. 116
Kruit, P. C. van der. 1971. *Astron. Astrophys.* 15:110
Kruit, P. C. van der. 1973a. *Nature Phys. Sci.* 243:127
Kruit, P. C. van der. 1973b. *Ap. J.* 186:807
Kruit, P. C. van der. 1973c. *Astron. Astrophys.* 29:263
Kruit, P. C. van der. 1974a. *Ap. J.* 188:3
Kruit, P. C. van der. 1974b. *Ap. J.* 192:1
Kruit, P. C. van der. 1975. *Ap. J.* 195:611
Kruit, P. C. van der. 1976a. *Astron. Astrophys.* 49:161
Kruit, P. C. van der. 1976b. *Astron. Astrophys. Suppl.* 25:527
Kruit, P. C. van der. 1976c. *Astron. Astrophys.* 52:85
Kruit, P. C. van der. 1977a. *Astron. Astrophys.* 59:366
Kruit, P. C. van der. 1977b. *Astron. Astrophys.* 61:171

Kruit, P. C. van der. 1978. See Bosma 1978a, Pap. I. 4
Kruit, P. C. van der, Allen, R. J. 1976. *Ann. Rev. Astron. Astrophys.* 14:417
Kruit, P. C. van der, Bosma, A. 1978a. *Astron. Astrophys.* In press
Kruit, P. C. van der, Bosma, A. 1978b. *Astron. Astrophys. Suppl.* In press
Kruit, P. C. van der, Bruyn, A. G. de. 1976. *Astron. Astrophys.* 48:373
Kruit, P. C. van der, Oort, J. H., Mathewson, D. S. 1972. *Astron. Astrophys.* 21:169
Krumm, N., Salpeter, E. E. 1977. *Astron. Astrophys.* 56:465
Lewis, B. M. 1968. *Proc. Astron. Soc. Aust.* 1:104
Lin, C. C., Shu, F. H. 1964. *Ap. J.* 140:646
Lin, C. C., Shu, F. H. 1966. *Proc. Natl. Acad. Sci. U.S.A.* 55:229
Love, R. 1972. *Nature Phys. Sci.* 235:53
Mathewson, D. S., Cleary, M. N., Murray, J. D. 1974. *Ap. J.* 190:291
Mayall, N. U. 1948. *Sky and Telesc.* 8, No. 3
Mayall, N. U. 1951. *Publ. Obs. Univ. Mich.* 10:19
Mayall, N. U., Aller, L. H. 1942. *Ap. J.* 95:5
McGee, R. X., Milton, J. A. 1966. *Austr. J. Phys.* 19:343
Minkowski, R. 1942. *Ap. J.* 96:306
Monnet, G., Deharveng, J. M. 1977. *Astron. Astrophys.* 58:L1
Morton, D. C., Andereck, C. D. 1976. *Ap. J.* 205:356
Muller, A. B. ed. 1971. *The Magellanic Clouds.* Dordrecht: Reidel
Münch, G. 1959. *Publ. Astron. Soc. Pac.* 17:101
Newton, K., Emerson, D. T. 1977. *MNRAS* 121:573
Nordsieck, K. H. 1973a. *Ap. J.* 184:719
Nordsieck, K. H. 1973b. *Ap. J.* 184:735
Oort, J. H. 1974. See Allen et al. 1973, p. 375
Oort, J. H. 1975. *Structure and Evolution of Galaxies*, ed. G. Setti, p. 112. Dordrecht: Reidel
Oort, J. H. 1977. *Ann. Rev. Astron. Astrophys.* 15:295
Ostriker, J. P., Peebles, P. J. E., Yahil, A. 1974. *Ap. J.* 193:L1
Pease, F. G. 1915. *Publ. Astron. Soc. Pac.* 27:239
Pease, F. G. 1916, *Proc. Natl. Acad. Sci. U.S.A.* 2:517
Pease, F. G. 1918. *Proc. Natl. Acad. Sci. U.S.A.* 4:21
Pellet, A. 1976. *Astron. Astrophys.* 50:421
Peterson, C. J., Rubin, V. C., Ford, W. K., Thonnard, N. 1976. *Ap. J.* 208:662
Peterson, C. J., Rubin, V. C., Ford, W. K., Thonnard, N. 1978. *Ap. J.* 219:21
Prévot, L. 1973. *Astron. Astrophys.* 28:165
Roberts, M. S. 1966. *Ap. J.* 144:639
Roberts, M. S. 1968. *Ap. J.* 151:117
Roberts, M. S. 1972. See Davies 1972, p. 12
Roberts, M. S. 1975a. See Burbidge & Burbidge 1975, p. 309
Roberts, M. S. 1975b. See Baldwin 1975, p. 331
Roberts, M. S. 1976. *Comments Astrophys.* 6:105
Roberts, M. S., Rots, A. H. 1973. *Astron. Astrophys.* 26:483
Roberts, M. S., Whitehurst, R. N. 1975. *Ap. J.* 201:327
Roberts, M. S., Whitehurst, R. N., Cram, T. R. 1978. See Bosma 1978a, Pap. III. 4
Roberts, W. W. 1969. *Ap. J.* 158:123
Roberts, W. W., Roberts, M. S., Shu, F. H. 1975. *Ap. J.* 196:381
Rogstad, D. H. 1971. *Astron. Astrophys.* 13:108
Rogstad, D. H., Lockhart, I. A., Wright, M. C. H. 1974. *Ap. J.* 193:309
Rogstad, D. H., Shostak, G. S. 1971. *Astron. Astrophys.* 13:99
Rogstad, D. H., Shostak, G. S. 1972. *Ap. J.* 176:315
Rogstad, D. H., Shostak, G. S., Rots, A. H. 1973. *Astron. Astrophys.* 22:111
Rogstad, D. H., Wright, M. C. H., Lockhart, I. A. 1976. *Ap. J.* 204:703
Rots, A. H. 1974. PhD thesis, Univ. of Groningen, The Netherlands
Rots, A. H. 1975. *Astron. Astrophys.* 45:43
Rots, A. H., Shane, W. W. 1975. *Astron. Astrophys.* 45:25
Rubin, V. C., Ford, W. K. 1970. *Ap. J.* 159:379
Rubin, V. C., Ford, W. K. 1971. *Ap. J.* 170:25
Rubin, V. C., Ford, W. K., Kumar, C. K. 1973. *Ap. J.* 181:61
Rubin, V. C., Ford, W. K., Peterson, C. J. 1975. *Ap. J.* 199:39
Rubin, V. C., Ford, W. K., Peterson, C. J., Oort, J. H. 1977. *Ap. J.* 211:693
Salpeter, E. E. 1978. See Bosma 1978a, Pap. I. 3
Sancisi, R. 1975. See Allen 1975a, p. 403
Sancisi, R. 1976. *Astron. Astrophys.* 53:159
Sancisi, R. 1978. See Bosma 1978a, Discuss. I. 3
Sancisi, R., Allen, R. J., Albada, T. S. van. 1974. See Allen 1975a, p. 295
Sandage, A. R. 1961. *The Hubble Atlas of Galaxies.* Carnegie Institution of Washington
Sandage, A. R., Freeman, K. C., Stokes, N. R. 1970. *Ap. J.* 160:831
Sanders, R. H., Bania, T. M. 1976. *Ap. J.* 204:341
Sargent, W. L. W. 1977. *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley, R. B. Larson, p. 427. Yale Univ. Obs.
Scheiner, J. 1899. *Ap. J.* 9:149

Schommer, R. A., Sullivan, W. T. III. 1976. *Astrophys. Lett.* 17:191
Schwarz, U. J. 1978. *Astron. Astrophys.* In press
Schweizer, F. 1975. See Allen 1975a, p. 339
Schweizer, F. 1976. *Ap. J. Suppl.* 31:313
Schweizer, F. 1977. *Ap. J.* 211:324
Schweizer, F. 1978. *Ap. J.* 220:98
Seielstad, G. A., Wright, M. C. H. 1973. *Ap. J.* 184:343
Segalovitz, A. 1975. *Astron. Astrophys.* 40:401
Segalovitz, A. 1976. PhD thesis, Univ. of Leiden, The Netherlands
Segalovitz, A. 1977. *Astron. Astrophys.* 61:59
Sérsic, J. L., Carranza, G., Pastoriza, M. 1972. *Astrophys. Space Sci.* 19:469
Shane, W. W. 1975. See Allen 1975a, p. 217
Shane, W. W. 1977. *Bull. Am. Astron. Soc.* 9:362
Shane, W. W. 1978. See Bosma 1978a, Discuss. III. 3
Shane, W. W., Bystedt, J. 1978. See Bosma 1978a, Pap. II. 2
Shobbrook, R. R., Robinson, B. J. 1967. *Aust. J. Phys.* 20:131
Shostak, G. S. 1973. *Astron. Astrophys.* 24:411
Shostak, G. S. 1974. *Astron. Astrophys.* 31:97
Shostak, G. S. 1975. *Ap. J.* 198:527
Shostak, G. S. 1977. *Astron. Astrophys.* 58:L31
Shostak, G. S. 1978. *Astron. Astrophys.* In press
Shostak, G. S., Rogstad, D. H. 1973. *Astron. Astrophys.* 24:405
Shostak, G. S., Weliachew, L. 1971. *Ap. J.* 169:L71
Shu, F. H. 1974. *Instellar Medium*, ed. K. Pankau, p. 219. Dordrecht: Reidel
Siefert, P. T., Gottesman, S. T., Wright, M. C. H. 1975. See Allen 1975a, p. 425
Simkin, S. M. 1970. See Freeman 1970b, p. 79
Simkin, S. M. 1972. *Bull. Am. Astron. Soc.* 4:214
Simkin, S. M. 1974. *Bull. Am. Astron. Soc.* 6:321
Simkin, S. M. 1975a. *Ap. J.* 195:293
Simkin, S. M. 1975b. *Ap. J.* 200:567
Slipher, V. M. 1914. *Lowell Obs. Bull.* II, No. 12
Slipher, V. M. 1915. *Pop. Astr.* 23:23
Smith, M. C., Weedman, D. W. 1971. *Ap. J.* 169:271
Smith, M. C., Weedman, D. W. 1972. *Ap. J.* 177:595
Smith, M. C., Weedman, D. W. 1973. *Ap. J.* 179:461
Solinger, A., Morrison, P., Markert, T. 1977. *Ap. J.* 211:707
Stockton, A. 1974a. *Ap. J.* 187:219
Stockton, A. 1974b. *Ap. J.* 190:L47
Toomre, A. 1977. *Ann. Rev. Astron. Astrophys.* 15:437
Toomre, A., Toomre, J. 1972. *Ap. J.* 178:623
Tully, R. B. 1974a. *Ap. J. Suppl.* 27:415
Tully, R. B. 1974b. *Ap. J. Suppl.* 27:437
Tully, R. B. 1974c. *Ap. J. Suppl.* 27:449
Tully, R. B., Bottinelli, L., Fisher, J. R., Gouguenheim, L., Sancisi, R., Woerden, H. van. 1978. *Astron. Astrophys.* 63:31
Tully, R. B., Fisher, J. R. 1977. *Astron. Astrophys.* 54:661
Turner, E. L., Ostriker, J. P. 1977. *Ap. J.* 217:24
Ulrich, M.-H. 1974. See Allen et al. 1973a, p. 279
Ulrich, M.-H. 1975. *Publ. Astron. Soc. Pac.* 87:965
Ulrich, M.-H. 1978. *Ap. J.* 219:424
Vaucouleurs, G. de. 1977. See Sargent 1977 p. 43
Vaucouleurs, G. de, Freeman, K. C. 1973. *Vistas in Astronomy* 14:163
Vaucouleurs, G. de, Vaucouleurs, A. de. 1971. *Astrophys. Lett.* 8:17
Vaucouleurs, G. de, Vaucouleurs, A. de, Freeman, K. C. 1968. *MNRAS* 139:425
Vaucouleurs, G. de, Vaucouleurs, A. de, Pence, W. 1974. *Ap. J.* 194:L119
Veny, J. B. de, Goad, J. W., Goad, L. E. 1976. *Bull. Am. Astron. Soc.* 8:568
Verschuur, G. L. 1975. *Ann. Rev. Astron. Astrophys.* 13:257
Visser, H. C. D. 1975. See Allen 1975a, p. 211
Visser, H. C. D. 1978a. See Bosma 1978a, Pap. II. 2
Visser, H. C. D. 1978b. PhD thesis, Univ. of Groningen, The Netherlands
Wakamatsu, K. 1976. *Publ. Astron. Soc. Jpn.* 28:397
Walker, M. F. 1968. *Ap. J.* 151:71
Warner, P. J., Wright, M. C. H., Baldwin, J. E. 1973. *MNRAS* 163:163
Weliachew, L. 1969. *Astron. Astrophys.* 3:402
Weliachew, L., Gottesman, S. T. 1973. *Astron. Astrophys.* 24:59
Weliachew, L., Sancisi, R., Guélin, M. 1978. *Astron. Astrophys.* In press
Whitehurst, R. N., Roberts, M. S., Cram, T. R. 1978. See Bosma 1978a, Pap. III. 5
Williams, T. B. 1977. *Ap. J.* 214:685
Winter, A. J. B. 1975. *MNRAS* 172:1
Woerden, H. van, Bosma, A., Mebold, U. 1975. See Allen 1975a, p. 483
Wolf, M. 1914. *Vierteljahresschrift Astron. Gesell.* 49:162
Wright, M. C. H. 1971. *Astrophys. Lett.* 7:209
Wright, M. C. H., Warner, P. J., Baldwin, J. E. 1972. *MNRAS* 155:337
Yoshizawa, M., Wakamatsu, K. 1975. *Astron. Astrophys.* 44:363