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History of our Understanding of a Spiral Galaxy: Messier 33

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INTRODUCTION

Messier 33 (= NGC 598) in the constellation Triangulum has the largest angular size of any late-type spiral galaxy. Only three other extragalactic objects, the Magellanic Clouds and Messier 31 in Andromeda, exceed the apparent dimensions of M33. And only M31 is also visible from the northern hemisphere. The large size and favourable inclination of M33 make it an excellent object for study. Our own Galaxy, the Milky Way, has traditionally been compared to the Andromeda galaxy. However, several recent observational results indicate that the Milky Way may be later in morphological type than M31. Hence the best model for our Galaxy may turn out to be a judicious interpolation between models obtained for M31 and M33.

THE ISLAND UNIVERSE THEORY

The idea that our Sun is just one of myriads of stars in a huge stellar system, the Milky Way, and that there may be many other stellar systems of equal rank outside the Milky Way can be traced back to the early eighteenth century (1). These early speculations* by the

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*Swedenborg wrote in the first chapter of the third part of his *Principia:*

> 'The common axis of the sphere or starry heaven seems to be the galaxy, where we perceive the greatest number of stars. . . . There may be innumerable spheres of this kind or starry heavens in the finite universe. These may be associated one with the other . . . and the whole visible starry heaven is perhaps but a point in respect to the universe. The objects comprehended within the range of our bodily vision are perhaps few; the greater number can be comprehended only by the mind. This very starry heaven, stupendous as it is, forms, perhaps, but a single sphere, of which our solar vortex constitutes only a part; for the universe is finited in the infinite. Possibly there may be other spheres without number similar to those we behold; so many indeed and so mighty, perhaps, that our own may be respectively only a point; for all the heavens, however many, however vast, yet being but finite, and consequently having their bounds, do not amount even to a point in comparison with the infinite.'

An interesting sidelight is cast by this excerpt from the following chapter, which foreshadows the idea of continuous creation contained in the hypothesis of the steady-state universe:

> 'Nor can she [nature] relatively equal or occupy a point of the infinite. Hence new heavens one after the other may arise; in these heavens, new vortices and world-systems; in these world-systems, new planets; around the planets, new satellites; and in this manner, at the will of the Deity, new creations may arise in endless succession.'

Swedish philosopher, Emanuel Swedenborg (2) had no basis in actual observations. Yet they are remarkably close to the present-day views of the cosmos. Thomas Wright of Durham in England, writing at the middle of the same century (3), conceived the idea apparently independently and was the first to appeal to observational evidence in support of it*. The best-known of the early exponents of the 'island universe' theory are the German philosopher Immanuel Kant (4), who acknowledged his indebtedness to the ideas of Wright, and the English astronomer, Sir William Herschel, who was the first to bring observational techniques to bear specifically on the study of nebulae and clusters of stars. In contrast, Messier compiled his catalogue of nebulae and clusters, which predates Herschel's work, primarily as a list of 'nuisances' to be avoided in his search for new comets (5).

At first it was not possible observationally to distinguish between gaseous nebulae and stellar aggregations, and it was thought that all nebulae were groups of stars—some of them so distant that individual stars could not be resolved. Since Herschel (6) was prepared to allow a wide range of nebular sizes, from those comprising only a few stars to systems of equal rank to the Milky Way (among which he included M33, as well as M17, M31, and Orion), he attempted to estimate the distances to nebulae on the basis of the amount of incipient resolution into stars. Then he found (7) the planetary nebula NGC 1514 which, from its appearance (8), was obviously a single star associated with faint nebulosity, a 'nebulous star'. For this reason, and from the fact that star counts in selected regions ('gauges') did not enable him to penetrate to the outside of the Milky Way, Herschel totally revised his thinking, now maintaining (9) that all nebulae were small compared to the Milky Way and were encompassed within it. The controversy between the two views was not to be resolved for more than a century after his death in 1822.

The observations by the Earl of Rosse with his 72-inch reflector raised the fortunes of the island-universe theory again. In 1845 he found the spiral nature of M51. His paper in 1850 (10) contained drawings of five spiral nebulae, including M33 (see Plate I), and listed fourteen more†. He also remarked that some of these spirals could

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*'That this in all Probability may be the real Case, is in some Degree made evident by the many cloudy Spots, just perceivable by us, as far without our starry Regions, in which tho' visibly luminous Spaces, no one Star or particular constituent Body can possibly be distinguished; those in all likelyhood may be external Creation, bordering upon the known one, too remote for even our Telescopes to reach.'

†Rosse's second paper (11) contains a drawing of M33 in which the spiral pattern is delineated over a region ~20′ in diameter, in good agreement with the most prominent arms seen on modern photographs. See Plate IIa and IIb.

PLATE I

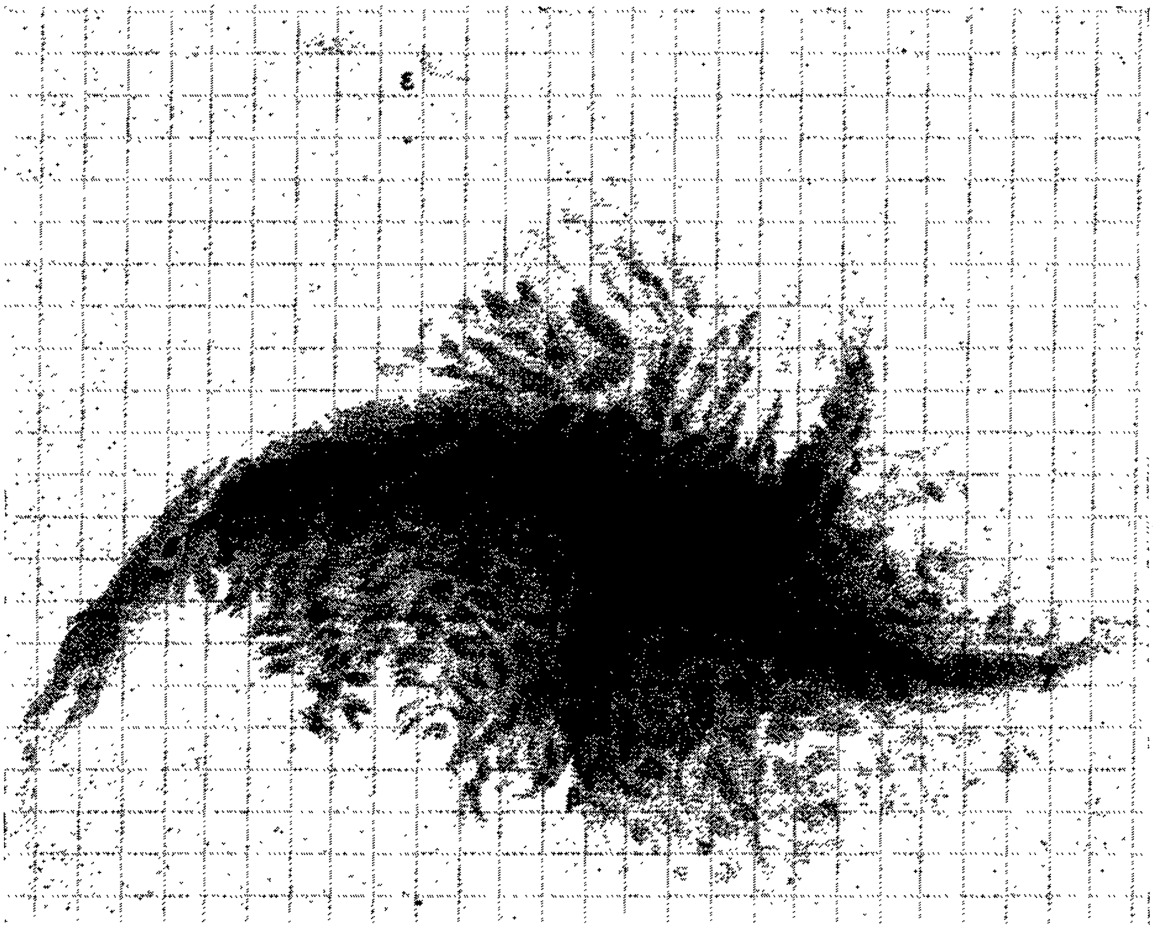


Plate XXXVI. Fig. 5, H. 131—This figure represents the central portion of a very large nebula. The nebula itself has not been sufficiently examined, but as yet no other portion appears to have a spiral, or indeed any regular arrangement. The sketch is not very accurate, but represents sufficiently well the general character of the central portion.

'September 6, 1849—A spiral.

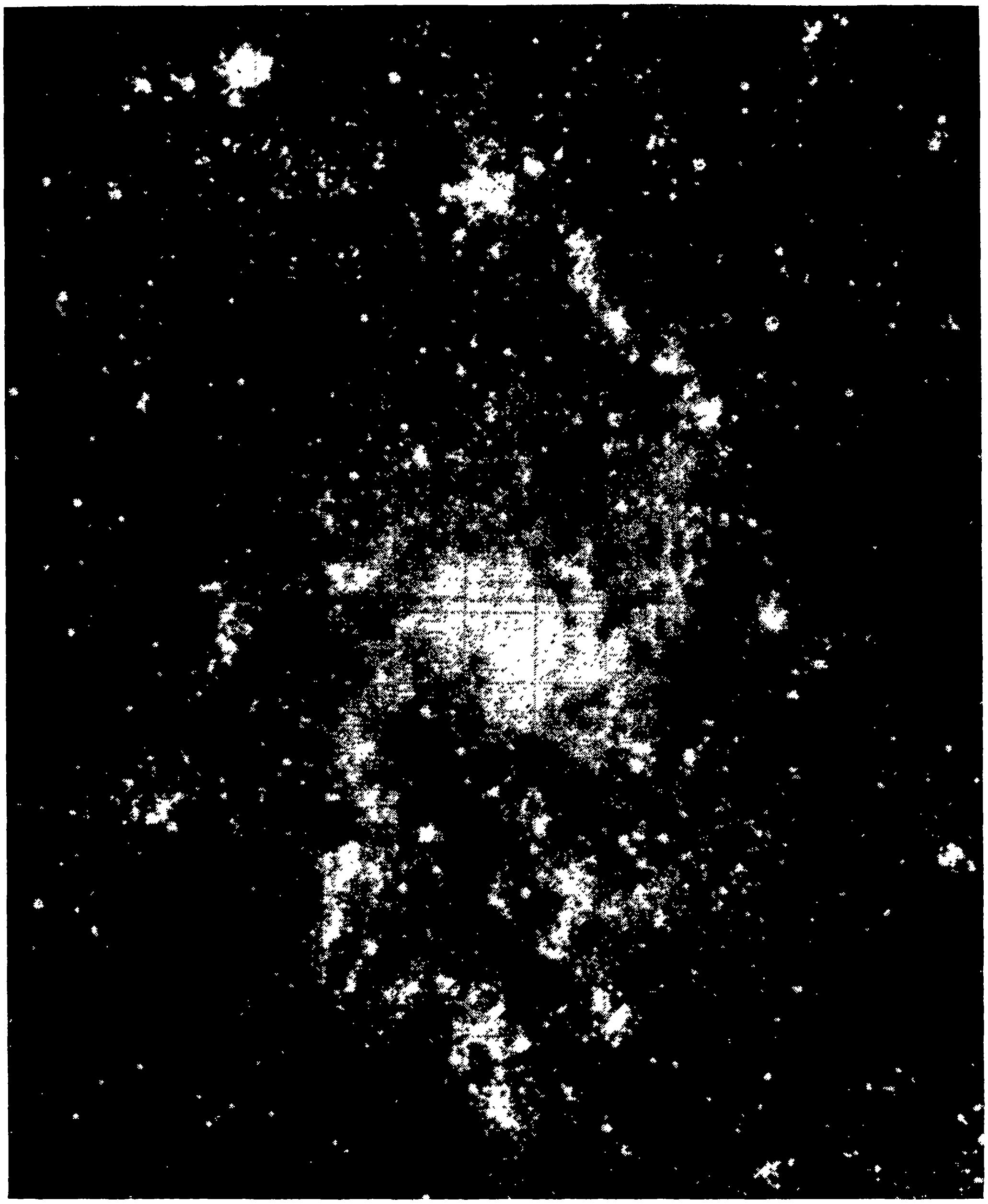
'September 16, 1849—New spiral; α the brightest branch; γ faint; δ short but pretty bright; β pretty distinct; ε but suspected; the whole involved in faint nebula which probably extends past several knots which lie about it in different directions. Faint nebula seems to extend very far following: drawing taken.

'September 10, 1849—An attempt at a drawing taken: fog.

'October 1849—The whole nebula in flocculi.'

The Earl of Rosse's drawing and description of Messier 33 (**10**).

PLATE IIb



The photograph, reproduced to the same scale as the drawing, was obtained with the Mt Palomar 48-inch Schmidt telescope on an emulsion sensitive to red light.

be resolved into stars†. On this basis, and using the star counts made by the Herschels, Alexander (**12**) suggested 'that the Milky Way and the stars within it together constitute a spiral with several (it may be *four*) branches', and traced the branches across the sky. But, in his essay on the nebular hypothesis (**13**), Herbert Spencer argued that since all stars are of similar sizes, all nebulae should be of similar sizes; and if the nebulae are actually stellar aggregations, then the apparently largest and presumably closest should be resolvable while the smallest and farthest should remain unresolved. In arguing that many quite small nebulae could in fact be resolved, Spencer mistook small clusters for nebulae. However, this was not immediately recognized.

In 1864, Sir William Huggins (**14**) observed several nebulae with a spectroscope, finding first an emission-line spectrum for the planetary nebula NGC 6543 and, a few nights later, a continuous spectrum with a hint of absorption features for the great Andromeda nebula. This showed that nebulae could be divided into two fundamentally distinct classes: those that were clouds of luminous gas and those that were stellar aggregations. All of the spiral nebulae were found to belong to the latter class. The conclusive evidence of this was presented in 1899 by Scheiner (**15**) in the form of the first good-quality spectrogram of a spiral nebula, M31.

The application of photography to studies of nebulae at the turn of the century made it possible to get more detailed pictures of the form of the spiral nebulae. The pioneering work in this field was done by the Irish amateur astronomer Isaac Roberts (**16a, b**) and by J.E.Keeler with the 36-inch Crossley reflector of the Lick Observatory (**17**). On the basis of these photographs, the spiral nebulae were subclassified into a 'condensed' type, showing condensations or knots of incipient resolution over the entire face of the nebula, and an 'uncondensed' type, showing incipient resolution only in the outermost parts of the nebula, if at all. The prototypes of the two groups were M33 and M31, respectively. Dreyer (**18**), using photographs taken by Roberts, published a catalogue of the condensations in M33 with the intent that it form a basis for determining whether there were any changes in the nebula in the course of time. Von der Pahlen (**19**) attempted to fit the forms of the arms of spirals to mathematical curves. He found that the two main arms of M33 fit logarithmic spirals quite well, but that they had different rates of coiling and that they were not 180° apart. Wolf and Ernst (**20a, b**) catalogued 517 knots of nebulosity in a region centred on M33, extending over a diameter of several degrees but

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†While it is conceivable that Rosse could have resolved the brightest individual stars in M33, in the more distant spirals (and probably also in M33) what he thought were stars must have been compact clusters or associations.

omitting the portion within 25′ of its nucleus. They found that the nebulae tended to concentrate in patterns which looked like extensions of the spiral arms so prominent in the inner part of M33. They claimed that the spiral pattern could be followed over a region 8° in diameter and concluded that M33 must therefore be quite nearby.

In 1914, Slipher (**21**) reported a radial velocity of $-300\,\mathrm{km\,s^{-1}}$ for M31, and Wolf (**22**) reported the first spectrographic measurements of internal motions of spirals, finding rotational velocities of $100\,\mathrm{km\,s^{-1}}$ in M81. In a larger-scale survey of the motions of spirals, Slipher (**23**) noted that their average velocity was roughly 25 times as large as the average stellar velocity, larger than for any other class of astronomical objects. He also found large internal motions, evidenced by a rotational velocity of the edge-on spiral NGC 4594 of $100\,\mathrm{km\,s^{-1}}$ 20″ from the nucleus. Pease (**24**), (**25**) confirmed the finding of large internal motions in spirals by measuring a difference of roughly $200\,\mathrm{km\,s^{-1}}$ between the radial velocities of the nucleus of M33 and of NGC 604, a bright condensation 10′ from the nucleus. The large systemic radial velocities indicated that the spirals could not be gravitationally bound by the Milky Way, and were thus at least not permanent members of it. The radial-velocity measurements of internal motions, if they could be combined with proper-motion data, would provide a direct measurement of the distances of the spirals.

During the first few years the Mt Wilson 60-inch telescope was in operation, Ritchey had obtained the best nebular photographs yet. His pictures of the condensed type of spirals showed many points in the nebulae which could be measured for proper motion. Second epoch plates were taken and measured by van Maanen. In 1916 he reported (**26**) finding motions in M101 which could be interpreted either as rotation or as outward streaming along the spiral arms. In either case, the fact that proper motions could be measured in the spirals indicated that they were nearby objects. His paper on M33 (**27**) contains a summary of his measurements and interpretations. To provide a check on these critical measurements, Lundmark independently remeasured the more than 400 points on van Maanen's plates of M33. Although his results correlated well with van Maanen's with respect to both direction and relative size of proper motion, the absolute scale of Lundmark's proper motions was less than 1/10 as large as those van Maanen had measured (**28**).

Meanwhile, evidence supporting the extragalactic interpretation of spiral nebulae began to mount up. In 1917, Ritchey's first photographic discovery of a nova in a spiral nebula (**29**), spurred Ritchey (**30**) and Curtis (**31**) to examine the large plate collections of Mt Wilson and Lick Observatories, where they found a score of others that had gone undetected in previous years, including two in M31. Systematic surveys over the next two years produced 14 additional novae in M31, but none in any other spiral. These formed a homogeneous group, all peaking at about $m_{pg} = 17$, about 10 magnitudes fainter than the visually detected nova S Andromedae of 1885 in M31. S And, on the other hand, was the only nova in M31 which conformed to the pattern of the novae discovered in other spirals, all of which had light outputs which were appreciable fractions of the total light outputs of the associated nebulae. At this time there was no compelling reason to choose either type of nova to represent the analogue of the galactic novae.

In 1921, Lundmark (**32**) found that counts of stars brighter than $m_{pg} = 15{\cdot}7$ in the field of M33 were not influenced by its presence. Hence M33 had to be farther away than the average $15^{m}{\cdot}7$ star, roughly 3 kpc. Moreover, if the brightest stars in M33 had absolute magnitudes of -6, it had to be 300 kpc away. In 1922, Duncan (**33**) discovered three recurrent variable stars in M33, the first found in any spiral. He also reported a suspected nova. By the end of 1924, Hubble (**34**) had assembled data on 47 variables in M33, 22 of which were Cepheids obeying the same period–colour-index and period–amplitude relations as the Cepheids in the Milky Way and the Magellanic Clouds. Applying the period–luminosity law, Hubble derived a distance of 285 kpc to M33, and a comparable result from similar data for M31. These distances agreed with those derived from the brightest non-variable stars and with those derived by choosing to identify the fainter of the two types of novae in M31 with galactic novae; S And and the novae in the other spirals were called supernovae. Star counts in M33 (**35**), coupled with the Cepheid distance scale, showed that its luminosity function agreed with Kapteyn's luminosity function for the MilkyWay, and thus appeared to settle the island-universe controversy. The one remaining loose end was the question of the reality of van Maanen's rotations. This was decided negatively on the basis of plates of M33 and M74 from the Mt Wilson 100-inch telescope (**36a, b, c**).

MODERN STUDIES OF M33

Morphology

The morphological type of M33 has been classified on all the existing systems: Sc (**37**), Sc+ (**38**), Sc II-III (**39**), SA(s)cd (**40**), fS3 or fS4 (**41a, b**), and L; ટટcd, Ha (**42**). Taken together, these indicate that M33 is a late-type right-hand ordinary (non-barred) spiral galaxy, with an apparent axial ratio of roughly 2 : 1, with an indefinite number of long, moderately broad, patchy spiral arms that can be traced directly into the nuclear region (which has an F-type spectrum), and with a smooth underlying haze or halo. Vorontsov-Velyaminov (**43**) noted that the spiral arms could be traced to within 20″ (75 pc) of the nucleus.

Photometry

Whitford (44) measured M33 photoelectrically through a 54′ circular diaphragm, and obtained $m_{pg} = 6{\cdot}9$ after correction for foreground stars and conversion to the international scale. Stebbins and Whitford (45a, b, c) included M33 in their six-colour photoelectric photometry of galaxies. In all three studies they used diaphragms of fixed sizes, centred on the nucleus; none of the diaphragms was large enough to include more than a small central portion of M33. As expected from the composite nature of the spectrum, the colour indices showed both violet and red colour excesses when compared with the colours of an individual star. Tifft's (46) four-colour photometry and McClure's and van den Bergh's (47) five-colour photometry also included only the nuclear region of M33. Although one of the primary objectives of multicolour photometry of galaxies is to provide information on the relative numbers of different types of stars contributing to the light of the galaxies, no photometric model of the stellar population of M33 has yet appeared in the literature.

A different type of photometric study is surface photometry in one or a few colours to determine the orientation of a galaxy and the distribution of light within it. Seyfert (48) found that, in spite of the very patchy appearance of M33 in photographs, most of the light followed a very smooth distribution. The spiral arms were barely visible on NS and EW tracings of photographs in red and blue light. The arms were somewhat bluer than the nucleus. Patterson (49) discovered that the gradient of photographic luminosity followed an exponential law—photographic magnitude a linear function of radius—except within 6′ of the nucleus. From microphotometer tracings every 30° of position angle, she found a position angle of the major axis of 20°, an inclination of the galactic plane to the plane of the sky of 60°, and an integrated m_{pg} of 6·0 out to 30′. Because Danver (50) worked only with the bright, inner arms of the galaxy, his results for position angle and inclination disagreed with those of Patterson and of more recent studies. However, he also noted the difference in pitch angle of the two main spiral arms, cf. (19), and he found that isophotes crossed the north-preceding half of the minor axis farther away from the galactic nucleus than they crossed the south-following half. Currently, the definitive photometric studies of M33 are the photographic photometry by Holmberg (38), (51a, b) on the international system and the photoelectric photometry by de Vaucouleurs (52) on the *UBV* system. De Vaucouleurs found a position angle of 23°, an inclination of 55°, and a total m_B of 6·27.

Vashakidze (53) measured 13 per cent mean optical polarization for M33, which was in line with the trend he found of percentage polarization increasing with advancing morphological type in a sample of 11 galaxies.

Emission nebulae

The existence of emission nebulae within M33 has been known at least since Pease (**24**) obtained a spectrogram of NGC 604. Detection of these emission regions has been accomplished primarily by comparison of blue plates (sensitive to [O II] 3727 Å) and/or red plates (sensitive to Hα) to yellow plates and/or infra-red plates. Catalogues of emission regions have been compiled by Haro (**54**), Aller (**55a, b**), Shajn (**56**), and Sérsic (**57**). By means of narrow Hα interference filters Courtès and Cruvellier (**58a, b**) found many emission regions in the central portion of M33, which is burned out on plates obtained by more classical methods. Within the errors of measurement, the H II regions in M33 have the same chemical composition as those in our own Galaxy (**59a, b**), and the Magellanic Clouds (**60**). Most of the emission nebulae are of low excitation (**61**), but some higher-excitation regions are found farther from the nucleus (**62**). The linear diameters of the largest H II regions are quite similar to those in the LMC. They have been used as calibrators for a method of distance determination to the more distant galaxies (**63a, b**)–(**65**). The masses of the largest H II regions have been calculated by Shajn and Haze (**66a, b**). Their measurements yield, after conversion to the presently accepted distance scale, a mass of the order of $3 \times 10^6 \mathscr{M}_\odot$ for NGC 604, the largest H II region in M33. (All distance–dependent quantities have been recalculated for consistency with a distance of 720 kpc (**64**).)

In addition to the emission lines in the H II regions, a diffuse background of line emission has been found at 3727 Å (**67**) and at Hα and [N II] 6548, 6584 Å (**68**). The ratio of the [N II] lines to Hα indicates higher excitation for this diffuse component than for the classical H II regions.

Radio continuum

Radio-continuum radiation from M33 has been observed at frequencies between 159 MHz and 3 GHz (**69a–i**). Fig. 1 is a graph of the published values of the integrated flux density from M33 as a function of frequency. The integrated flux densities can be represented approximately by a power-law spectrum, $S_\nu = S_o\,(\nu/\nu_o)^\alpha$. The lines in the figure represent least-squares solutions for the power law: $S_o\,(\nu_o = 1\text{ GHz}) \approx 5$ flux units* and $\alpha \approx -1{\cdot}0$. The 4C catalogue (**70**) contains no source within 45′ of the position of the galaxy, indicating that at 178 MHz the emission is smoothly distributed over a region significantly larger than 1′ in extent. At centimetre wavelengths, the radiating region is $\sim 0^\circ{\cdot}5$ in diameter.

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*1 flux unit $= 10^{-26}$ W m^{-2} Hz^{-1}.

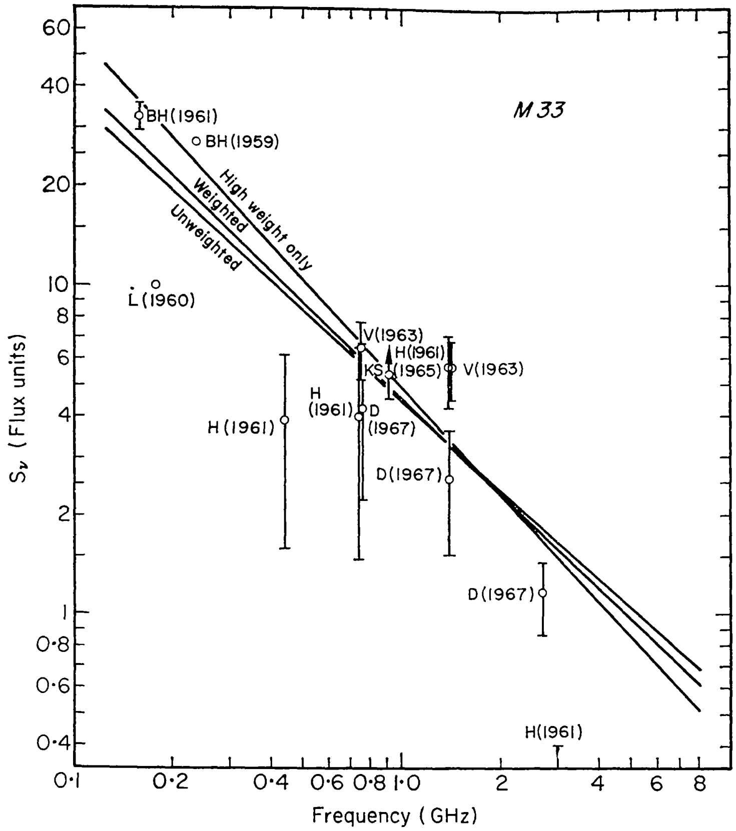

FIG. 1. The radio-continuum spectrum. The points are published integrated flux densities of M33, with mean errors indicated where known. The points are labelled with authors' initials and dates of publication (**69a–i**). The lines represent three different linear-least-squares regression curves of log S_ν upon log ν. All points were used in the 'weighted' and 'unweighted' solutions. In the 'weighted' solution, the four values obtained by mapping the galaxy (BH at 159 MHz, V at 750 and 1410 MHz, and D at 2795 MHz) were given double weight. Only these four points were used in the 'high weight only' solution.

Neutral hydrogen

The neutral-hydrogen distribution was found to extend 'far beyond the structure visible on the available photographs' (71) even in the earliest 21-cm line observations of M33. However, an attempt to find an H I link between M33 and its nearest neighbour, M31, was unsuccessful (72). The angular resolution of the early data was insufficient to provide any details of the hydrogen distribution. But, more recently, Davies (73) and Burke (73) noted that their observations with the 250-foot and 300-foot telescopes, respectively, indicated a ring-shaped distribution of the neutral hydrogen in M33. The radius of this ring has been placed between 15′ and 20′ (73), (74a, b), (75). However, the centre of the ring is displaced by a few minutes of arc from the optical centre of the galaxy (76), and there are other departures from axial symmetry. The most striking of these are a pair of 'wings' on the north-preceding and south-following ends of the galaxy, nearly 1° from the galactic centre (**75**).

Stellar content

Because there is a difference of several magnitudes between the photographic luminosities of the brightest stars of Populations I and II, the first stars to be resolved in external galaxies are Population I objects. The first individual stars recognized in M33 were Duncan's (**33**) three variables and a nova. Hubble (**34**), (**35**)—who at the time was interested primarily in determining the distance to M33—discussed this nova, Cepheids, and a luminosity function derived from star counts of selected fields within M33. Hubble and Sandage (**77**) found that the brightest variable stars (intermediate-type supergiants) formed a group with a small dispersion in luminosity, thus providing another distance criterion for galaxies. By comparing a colour–magnitude diagram of stars in M33 to a composite colour–magnitude diagram of young galactic clusters (Population I objects in our own Galaxy), Johnson and Sandage (**78**) rederived the distance to M33.

De Vaucouleurs (**79**) extended the star counts to cover the entire face of M33 down to 20th photographic magnitude ($m_B \leq 20{\cdot}2$ or $M_B \leq -4{\cdot}4$). On the basis of these counts, he found (**80**) the centre of the distribution of the brightest Population I stars to be displaced to the southwest of the optical centre. Vorontsov-Velyaminov (**43**), (**81a, b**) found that the supergiants in M33 tended to crowd together and form compact groups, 65 of which he catalogued. He stated that the dust in the spiral arms appeared to avoid close contact with such groups.

The first mention of the possible presence of Population II stars in M33 was Hubble's (**82**) discovery of 12–15 objects which he tentatively identified as globular clusters. He noted, however, that they were fainter and bluer than most globular clusters in M31 and our Galaxy Hiltner (**83**) performed *UBV* photometry on 23 clusters, including those found by Hubble. He suggested that they might be rich galactic clusters rather than globulars, but noted that, on the other hand, they might be counterparts of the faint blue globular cluster NGC 7492 in the Milky Way. These results were corroborated by Kron and Mayall (**84**), who included 4 clusters in M33 in their *PV* photometry. Vorontsov-Velyaminov (**43**) stated that the only trace of a Population II nucleus he could find for M33 was a feature no larger than a single globular cluster. Walker (**85a, b**) obtained an infra-red plate (103a-U+RG8) of M33, with a limiting magnitude between the apparent magnitudes of Populations II and I red giants, and a blue plate (103a-O+GG13) exposed to the same density for OB stars as the infra-red plate. Making a composite from the blue negative and an infra-red positive, Walker brought to light the existence of a smooth, elliptical distribution of Population II red giants in M33. From this evidence he argued that M33 must be just as old as M31, and that the difference in their morphological appearance was due solely to different initial conditions.

Kinematics

Although the rotation of M33 was discovered in 1916 (**25**), the first study of the rotation appeared more than two decades later (**86a, b**). This study by Mayall and Aller was based upon the radial velocities of 25 emission nebulae, determined from low-dispersion spectrograms. The rotation curve was roughly linear within 15′ of the nucleus, reached a peak of ~ 105 km s^{-1} radial velocity (~ 125 km s^{-1} circular velocity) between 15′ and 20′, and decreased thereafter. Models of the mass distribution responsible for the observed rotation were discussed by various authors (**87a–h**) between 1941 and 1957. Because of the limited accuracy of the data, quite different models could yield satisfactory agreement. In contrast to the situation in M31 and the Milky Way, no rapidly rotating nucleus has been seen in M33 (**88a, b**). The observations of M33 were of limited usefulness in the discussions (**89a, b, c**), (**90**) of whether spiral arms lead or trail in galactic rotation because of the difficulty in determining which side of M33 is closer to the observer. After the controversy had been settled in 1958 (**90**), de Vaucouleurs' photometric study of M33 (**46**) showed that its arms trailed, like those of the rest of the galaxies for which the sense of rotation could be determined.

New kinematical data for M33 were added by the observations of Dieter (**91**) and Volders (**92**) in the 21-cm line of neutral atomic hydrogen. These observations yielded much better velocity resolution than did the optical data. However, the positional accuracy of the measurements was quite low, since the half-power beam widths of the telescopes were respectively 53′ and 34′. The masses derived in the two radio studies ($\sim 2 \times 10^{10} \mathscr{M}_{\odot}$) were both significantly larger than the masses found from the Mayall and Aller data. Burke, Turner & Tuve (**93**) obtained 21-cm observations with angular and velocity resolution both improved over those available to Dieter and Volders, but restricted their study to the major and minor axes of M33. They found that the systemic velocities obtained from the observations along the two axes disagreed by 5 km s^{-1}, an amount which they stated 'is significant but is not understood'. They did not derive a mass for M33 from their observations.

Brandt (**94**) used 110 Å mm^{-1} spectrograms to determine radial velocities from the Hα emission of 24 H II regions in M33, mostly the same regions used by Mayall and Aller. Brandt's measurements indicated that the turnover point of the rotation curve lay beyond the outermost optical features within M33 (in disagreement with the earlier optical measurements). Because his measurements did not reach the turnover point of the rotation curve, he supplemented them with Dieter's and Volders' radio data, finding a total mass of $3{\cdot}9 \times 10^{10} \mathscr{M}_\odot$ for M33. Also, by truncating his model at appropriate distances from the centre of the galaxy, he found 'remarkably consistent' agreement between his results and all of the previous mass determinations. Takase and Kinoshita (**95**) combined the radio data with the older optical velocity measurements and found a significantly smaller total mass.

The most detailed kinematical study of M33 available is by Carranza *et al.* (**68**). Using Fabry-Perot interferograms of the Hα emission from M33, they measured 1048 points in the galaxy at dispersions of 15–30 Å mm^{-1}. They found an asymmetry between the northern and southern halves of the rotation curve; the mean of the two agreed with Brandt's measurements. Furthermore, in the southern half of the galaxy they found that the gas in the spiral arm appeared to be rotating more rapidly than the gas in the adjacent interarm region at the same distance from the nucleus.

The extensive 21-cm study by Gordon (**75**) with a beamwidth of 10′ confirmed the location of the peak of the rotation curve outside the optical picture of the galaxy. It also confirmed the existence of the asymmetry of the rotation curve and found departures from circular motion, particularly in the outer parts of M33. Gordon's value for the total mass of the galaxy was $4{\cdot}9 \times 10^{10} \mathscr{M}_\odot$, the increase over Brandt's value arising primarily from extrapolating a greater fraction of the mass in the outermost fringes of the galaxy.

CONCLUSION

Because of its nearness, and the fact that it is visible from the northern hemisphere, M33 is one of the two most intensively studied extragalactic objects. Observations of M33 figured prominently in the controversy over the island-universe theory, and in the proof that spiral nebulae are in fact galaxies similar in size to the Milky Way. As a giant stellar system, M33 displays many similarities with our own Galaxy. M33 is a weak nonthermal radio source. It is highly flattened and approaches circular symmetry both in the distribution and motions of its component stars and gas. The abundances of the chemical elements are similar to those found in the solar neighbourhood; both young and old populations of objects are represented. The most abundant gaseous constituent, neutral atomic hydrogen, is distributed in a broad ring with its maximum projected surface density well outside the most prominent optical features of the galaxy. These features, noted as a result of their high surface brightness, contribute only a small fraction of the total luminosity of M33. Most of the light is emitted by a smooth distribution of vast numbers of individually less luminous stars.

The differences between M33 and the Milky Way are mostly ones of degree rather than kind. M33 is the less massive of the two galaxies. Its spiral arms are less tightly wound. The young Population I objects seem relatively more numerous. The largest of the giant H II regions in M33 exceed in size any of the known emission regions in our Galaxy, and there are no recognized counterparts in the Milky Way of the H I 'wings' in M33.

In spite of our intensive study, there remain many gaps in our understanding of Messier 33. One of these, certainly, is the extent of the older population of stars in this late-type spiral. Another concerns the departures from circular symmetry in the kinematics, the explanation of which is very important to the understanding of the same puzzling phenomenon in our own Galaxy. The gathering of more quantitative data on the distribution of the various gaseous constituents of M33, in addition to the neutral atomic hydrogen, may shed light on the problems of the interstellar medium and of star formation. Without doubt there are many fertile fields for investigation, even in the nearest galaxies.

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