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A Spectroscopic Study of the Irregular Galaxy NGC 3067

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A spectroscopic analysis of the Type II Irregular galaxy NGC 3067 shows it to have an interstellar gas component of low density. Rotation curves give a mass of 1.8×10^{10} $M_\odot$ in the inner one third of the visible galaxy. A mass density of 1.5 $M_\odot$ pc^{-3} is higher than average but the mass-to-luminosity ratio 6.8, and the absolute visual magnitude −19.2 are consistent with mean values quoted for Type II Irregular galaxies.

INTRODUCTION

The Type II Irregular galaxies pose a number of significant astrophysical problems. Probably the most outstanding difficulty is caused by the fact that they do not constitute a homogeneous group. For example, some galaxies in this class such as NGC 4753 and NGC 3077 have luminosity distributions similar to those observed for E or SO galaxies, while others, such as NGC 972 and NGC 4433, are very similar to dusty inclined spirals. Still others have no morphological resemblance to normal galaxies.

Many of these galaxies including NGC 3067 have been classified as M 82-type by Markarian (1963). It, like others of its class, has an early type of stellar spectrum (F2) but red integrated colors (B-V ~ 0.62). The red colors may be explained by internal space reddening due to large quantities of dust. However, the significant absence of H II regions in many of them provides a sharp contrast with Type I Irregulars where the presence of dust, young stars, H II regions, and the blue colors seem to fit a consistent pattern expected for a system dominated by a Population I component.

Unlike many of the Type II Irregulars, NGC 3067 does appear to contain some condensations somewhat similar to H II regions as well as a general amorphous region emitting line radiation not unlike that expected from an H II region. The dust lanes in NGC 3067 are pronounced but irregular, and therefore compatible with the patterns observed in dusty spiral galaxies observed edge-on. This might be contrasted with the peculiarly filamentary structure of multiple dust lanes observed in the more spherical Type II Irregulars such as NGC 3077. NGC 3067 was reported to be a radio source by Heeschen and Wade (1964), who observed it at 750 and 1400 Mc/sec. The spectral index of −0.53 indicates it to be a non-thermal source. However, subsequent observations with higher spatial resolution (see Dixon 1970) seem to suggest that the true source of this radio emission is the quasar Ton 469 (3C 232).

OBSERVATIONS

The observational material on which this study is based consists of a series of unwidened spectra taken at different angles and centered on NGC 3067. These spectra were taken with the Cassegrain image-tube spectrograph on the 84-in telescope at Kitt Peak National Observatory, and consist of some plates covering the spectral region 3500–6000 Å and others covering the region 4800–6800 Å. All plates have a dispersion of approximately 132 Å/mm and were taken with an effective slit width of 1.6 arc sec. We list the details of the plates, including exposure times and the angles of orientation of the slit in Table 1.

Both absorption and emission lines are present in the spectra. The visible absorption lines, Na I D, Ca II H+K, and the Balmer series from H_δ to H_7 are generally blurred, in keeping with the description given by Humason *et al.* (1956). The emission lines appear to arise in the amorphous region of the galaxy and are not confined to visible condensations. The following emission lines are present: [O II] 3727; Hβ 4861; [O III] 4959, 5007; [N II] 6548, 6584; Hα 6562; [S II] 6716, 6731.

All lines appear to have similar spatial structure. The relative line strengths are similar to those observed in NGC 3955, which is an Irr II of similar

TABLE 1

Details of spectra

Plate no.	Spectral region	Exposure (min)	Slit angle (arc deg)
1884	Blue	90	106
1885	Blue	60	64
1886	Blue	64	16
1887	Red	90	116
1888	Red	31	64
1903	Red	40	106
1907	Red	140	106
1908	Red	150	64
1912	Red	120	16
1913	Red	120	147

morphology. The relative line strengths give some idea of the excitation conditions in the interstellar gas in NGC 3067. For example, the ratio I (5007+4959)/I (4861) is approximately 0.3. Furthermore, the ratio I (3727)/I (4959) is very large, and although we cannot make worthwhile quantitative estimates of excitation conditions from our spectra, these quantities suggest low excitation conditions in NGC 3067. Excitation class 2 (Aller 1956) seems to be indicated. For the [S II] lines we obtain a value of I (6716)/I (6730) of approximately 1.5. Although we cannot put precise numbers on the electron density that gives rise to this ratio, it seems clear from the work of Mendez (1965) that the medium is of very low density, perhaps no more than Ne $\sim 100/\text{cm}^3$. This is at least one order of magnitude lower than the value obtained for compact H II regions in the galaxy (see Schraml and Mezger 1969).

ROTATION AND MASS

From our spectroscopic plates we have measured rotation curves at five different position angles centered on the galaxy. By inspection of direct photographs we have estimated the major axis of the elliptical projection of the galaxy to have a position angle of 106 ± 2 arc deg. In the work described below we have assumed that the galaxy has circular symmetry in the plane of rotation, and have used the ratio of the minor to major axes in the galaxy image (0.401) to compute 66.5 arc deg as the angle between the line of sight and the axis of rotation.

The measured rotation curves at the different angles are given in Figures 1–6. Only emission lines have been measured. Data points of low weight not used in the analysis have been enclosed in parentheses. Since not all the spectra taken intersected at a common point on the galaxy, the zero point on the abscissa of each figure refers to the center of the slit for that particular plate. The actual slit positions and orientations on the plane of the sky are given in Figure 7. Figure 8 shows all the smoothed rotation curves reduced to real motions in the plane of the galaxy. From these figures, we see that there is good agreement between different lines on the same plate and between different plates. The rotation curve for Plate 1885 differs somewhat from the others. However, the final results are not sensitive to the inclusion of this material.

Some curves, especially those measured along the major axis, suggest that the turnover points in velocity may have been reached near the ends of the visible lines. If this is indeed true it means that most of the mass of the galaxy is contained within the limits defined by the end points of the strongest emission lines.

To proceed further we require a knowledge of the distance to NGC 3067. The only method open to us is to use the Hubble velocity-red shift relation. If we assume a value of 75 km/sec/Mpc for the Hubble constant, and a velocity of 1354 ± 40 km/sec of NGC 3067 (measured on our spectra by interpolating to the central point when the slit did not pass through it) relative to the galactic center, we obtain a distance of 18.1 mpc. Adopting the apparent integrated magnitude $m_b = 12.9$ given by de Vaucouleurs and de Vaucouleurs (1964), we see that NGC 3067 has an absolute integrated magnitude $M_v \sim -19.2$, corrected only for galactic absorption according to de Vaucouleurs and de Vaucouleurs (1964), which is similar to the mean values quoted by Chester and Roberts (1964) for Type II Irregulars. This result could be in error for two reasons. First, the recession velocity is small and therefore the random component may be large. Second, at the present time there still seems to be a not insignificant uncertainty in the value of the Hubble constant. Therefore, we judge this distance to be uncertain by at least a factor of 2.

The major axis of the elliptical projection on the

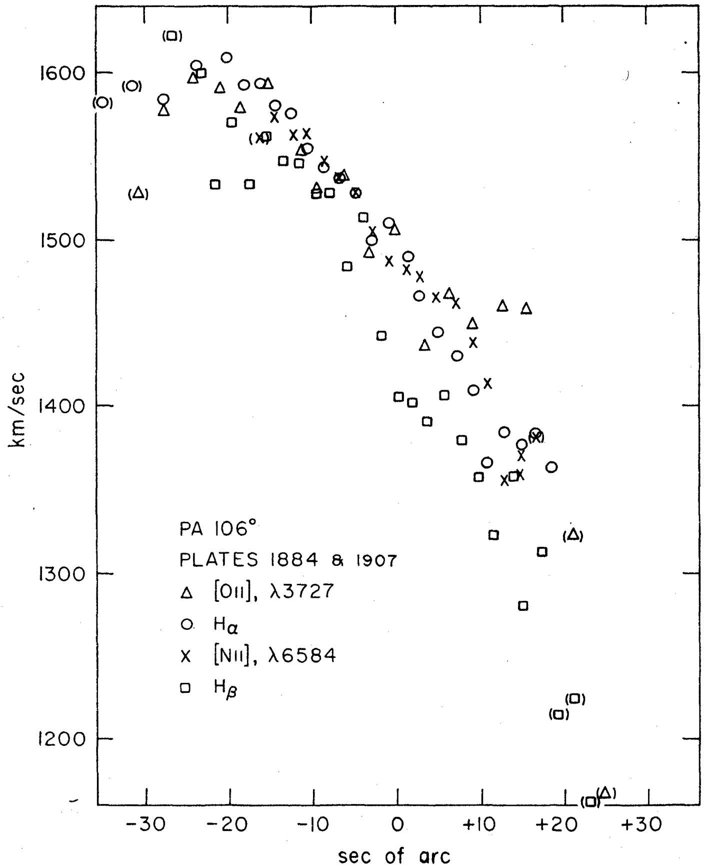

FIG. 1. Heliocentric velocities observed in NGC 3067 for position angle 106°. Velocities are uncorrected for both inclination of the galaxy and orientation of the slit. Abscissa is measured from the slit center.

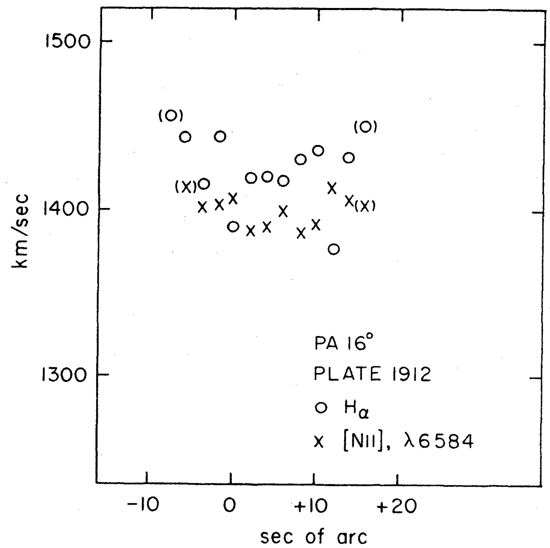

FIG. 2. The same as Figure 1 for position angle 16°.

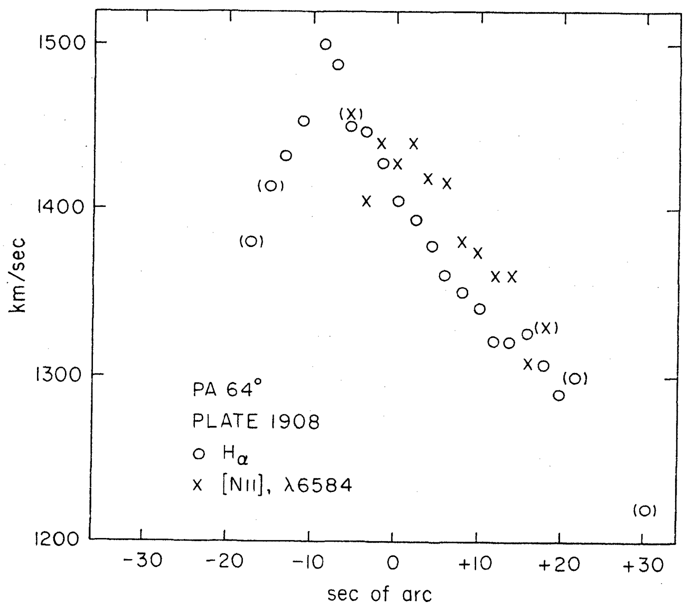

FIG. 3. The same as Figure 1 for position angle 64°, plate 1908.

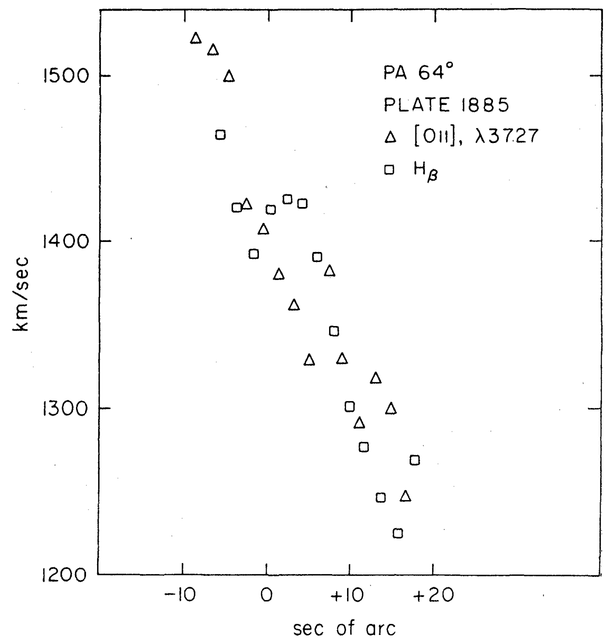

FIG. 4. The same as Figure 1 for position angle 64°, plate 1885.

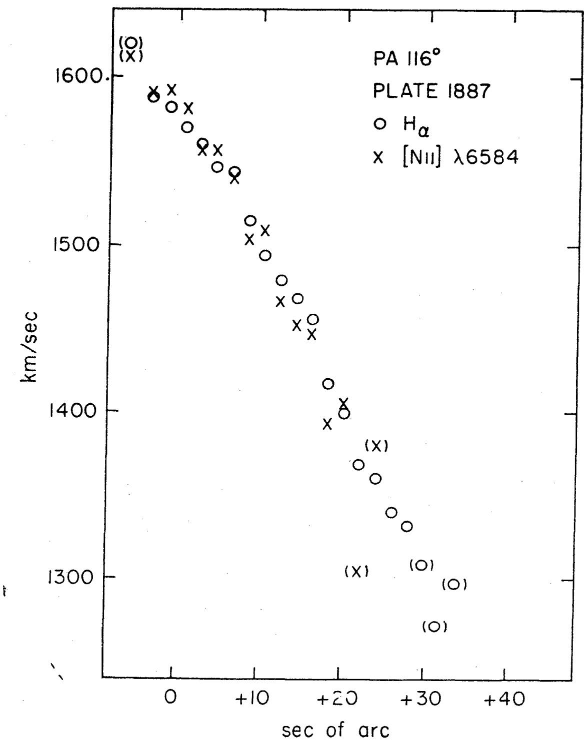

FIG. 5. The same as Figure 1 for position angle 116°.

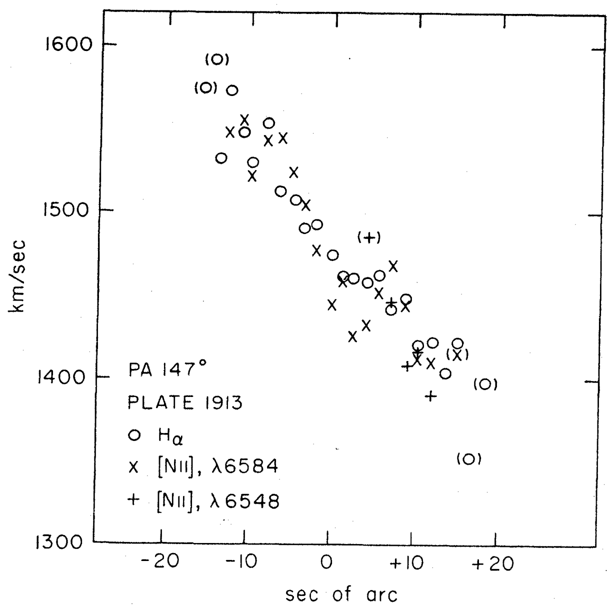

FIG. 6. The same as Figure 1 for position angle 147°.

sky of NGC 3067, 144 arc sec (de Vaucouleurs and de Vaucouleurs 1964), at the above distance corresponds to a linear distance of 12.7 kpc. This is consistent with the usually accepted mean diameters of Sa and Sb galaxies, as well as some Type II Irregular systems.

We use the relevant data discussed above to derive a mass for NGC 3067. Since our rotation curves show an approximately linear variation of velocity with distance, we have assumed that we can approximate the distribution of material interior to the outermost measurable point by an oblate spheroid of uniform density. We assume a value of 0.3 for the ratio of minor to major axis of this spheroid. The final mass is not very sensitive to the particular value of this parameter. The following formulation is appropriate for this configuration, and has been applied by Burbidge *et al.* (1959) to a study of NGC 1068. By balancing the centripetal force by the gravitational attraction at the equatorial surface of a solid oblate spheroid we obtain the expression for the mass contained within the spheroid, $M = (aV^2/G\alpha)$, where a is the semi-major axis and taken to be 1800 pc, c is the semi-minor axis, V is the tangential linear velocity, G is the gravitational constant, and

$$\alpha = \frac{3}{2}\frac{a^2}{a^2-c^2}\left\{\frac{a}{(a^2-c^2)^{1/2}}\cos^{-1}\left(\frac{c}{a}\right)-\frac{c}{a}\right\}.$$

This last expression arises in effect in the equation for the potential at the equatorial surface of an oblate spheroid and represents a correction factor that is applied to the case of a sphere; $V = (V_z/\sin\theta\cos\phi)$, where V_z is the measured line-of-sight velocity, θ is the angle between the line-of-sight and the axis of rotation of the galaxy, and ϕ is the angle in the plane of the galaxy between the major axis of the galaxy and the slit of the spectrograph.

Substitution of the values of the parameters discussed above in these equations gives a mass for NGC 3067 of $1.8\times10^{10}\,M_\odot$. A standard error of ±25 per cent comes from the scatter in the results obtained from 6 individual spectrograms all given equal weight. This mass is contained within an inner third or quarter of the linear dimension of the galaxy. Before we discuss the implications of this

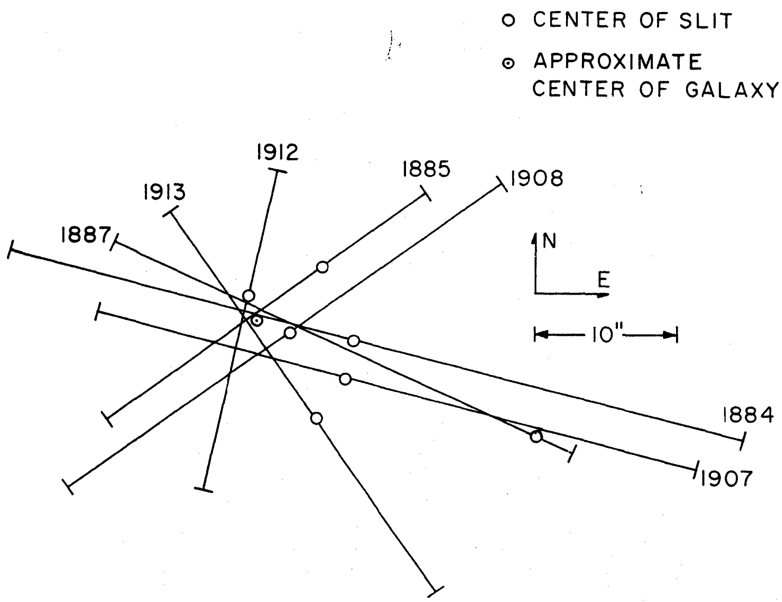

FIG. 7. The orientation of slits and slit centers on the plane of the sky for the plates used in this study. In each case, the slit length has been drawn to correspond to the maximum length of emission lines on the plate. The uncertainty in the position of the center of the galaxy is ± 3 arc seconds.

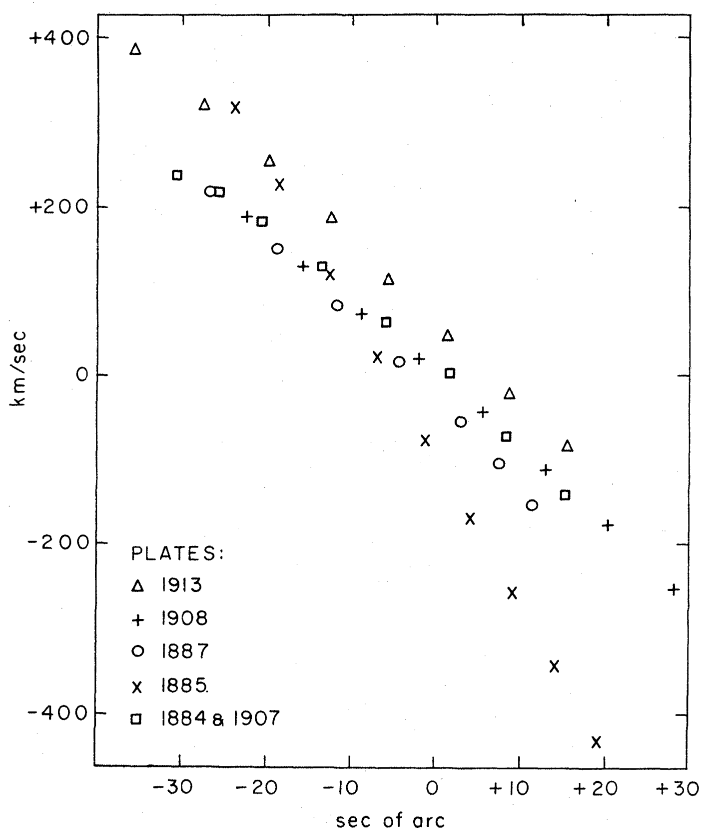

FIG. 8. Velocities relative to the center of mass of NGC 3067. Circular motion in the plane of the galaxy has been assumed. Plotted curves were computed from smoothed versions of those in Figures 1–6. Abscissa is positive on the E side of the galaxy.

result we can calculate the mass density in this region and the mass-to-light ratio M/L.

The density of the spheroid is

$$(10M/4\pi a^3) = 1.5\ M_\odot\ \mathrm{pc}^{-3} = 1.0 \times 10^{-22}\ \mathrm{gm\ cm}^{-3}.$$

This is not dissimilar to the mean density in the main body of M 31 obtained by Wyse and Mayall (1942), if we use the more modern distance scale. To determine the mass-to-light ratio we need to estimate the luminosity of the material inside the oblate spheroid. We make this estimate by using the statistical correction procedure by de Vaucouleurs and de Vaucouleurs (1964) for galaxies of different morphological types observed with different sized apertures. We conclude that the luminosity m_v inside a diameter of 48.3 arc sec would be 12.49 mag (correction taken as the mean of that for Irregular II and Sb galaxies). Hence we derive a mass-to-visual luminosity ratio $M_\odot/L_\odot$ for this volume of NGC 3067 to be 6.8.

In summary we see that the absolute magnitude, colors, mass, mass-to-light ratio, and dimensions of NGC 3067 are all consistent with mean values quoted for Type II Irregular systems. Although the mass density we derive is noticeably greater than the values usually quoted for all types of galaxies, it must be noted that this figure pertains to the innermost part of the galaxy, and therefore is almost certainly bound to be larger than a mean density averaged over the whole galactic volume. In any case it is lower ($\times 2$) than the value obtained by Burbidge *et al.* (1959) for the nucleus of the Seyfert galaxy NGC 1068.

The most significant part of this study is the derivation of a mass which, from all indications, is a reliable one. The mutual consistency and symmetry of rotation curves measured at different angles, and the absence of evidence for large scale random motions, lead us to believe that the mass determination is trustworthy. When we consider rotation curves measured for other symmetric systems such as NGC 7331 (see Rubin *et al.* 1965) it seems safe to conclude that the mass outside the oblate spheroid contributes at most an extra 50 per cent to the mass inside the spheroid, but only if we have established maximum velocity points on the rotation curves. Since this is not unequivocally clear from our data the amount of unobserved mass could be greater.

While the mass-to-light ratio seems consistent with an early type of stellar spectrum seen in Sc and Irr I galaxies, more detailed photometry will be required to elucidate the true nature of the stellar content of NGC 3067 and other Type II Irregular galaxies. Certainly the dynamics of the galaxy do not indicate an irregular system, but rather an ordered rotating one.

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