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Two-micron spectrophotometry of the galaxy NGC 253

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Summary. A very strong Brackett-γ hydrogen emission line, and the 2.3-μm CO stellar absorption feature have been measured in NGC 253. The presence and strength of the CO feature indicates that late-type giant stars produce most of the 2.2-μm continuum emission, while the rate of ionization implied by strength of the Brackett-γ line indicates that much, perhaps all, of the luminosity detected at far-infrared wavelengths originates from a large number of OB stars. As compared to the corresponding region of the Galaxy, the number of massive young stars in the central 200 pc of NGC 253 is 30 times greater, but the total mass of stars is roughly the same.

1 Introduction

NGC 253 is a southern Sc galaxy with a nucleus that is prominent at wavelengths from 2 to 300 μm. For an assumed distance of 3.4 Mpc, its bolometric luminosity is $2.8 \times 10^{10} L_\odot$ (Telesco & Harper 1979), which puts it intermediate in power between the Galaxy and a Seyfert galaxy. The nucleus at 10 μm and its associated radio source are both extended on a scale of 10 arcsec or 150 pc (Becklin, Fomalont & Neugebauer 1973; Rieke & Low 1975). At visible wavelengths the nucleus shows strong Hα emission with velocities indicative of expansion speeds of about 80 km/s (Ulrich 1978). Infrared spectrophotometry by Gillett *et al.* (1975) and by Russell, Soifer & Merrill (1977) show a 10-μm 'silicate' absorption feature, broad unidentified 3.3- and 11.3-μm features, and the 12.8-μm [Ne II] line. In the present paper we present spectrophotometry in the 2.2-μm window; the features of interest are the 2.17-μm hydrogen Brackett-γ line, and the 2.3-μm stellar CO absorption edge.

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2 Observations

Observations were made on 1976 July 13 and 14 on the 4-m telescope at CTIO using a continuously variable interference-filter wheel in conjunction with an indium antimonide photovoltaic detector. The observing system was that described by Wynn-Williams *et al.* (1978). In the present observations the spectral resolution was approximately 25 nm, and the diaphragm diameter was 13 arcsec. Over most of the spectral range, observations were spaced by 13 nm, but a higher sampling rate was employed near the Brackett-γ line. A correction of 0.05 mag per air mass was applied at all wavelengths.

3 Results

Fig. 1 shows the spectrum of the source measured at the position of maximum broad-band 2.2-μm emission. Each data point is the mean of observations taken on two days. Comparison of the two days' readings indicates that the relative error between nearby spectral points rarely exceeds 3 per cent, although the absolute calibration, via the B5 star κ Eridani, is accurate only to about 10 per cent.

Two spectral features can be seen in Fig. 1. The absorption feature at $\lambda > 2.3\ \mu$m is similar to that arising from CO molecules in the atmospheres of late-type giant stars (see, e.g. Frogel *et al.* 1978). The emission feature at 2.17 μm is the Brackett-γ recombination line of hydrogen; its strength, estimated from the area between the spectrum and the interpolated continuum, is $(5 \pm 2) \times 10^{-16}\ \mathrm{W\ m^{-2}}$. The error quoted reflects the uncertainty in determining the continuum level beneath the line.

4 Discussion

4.1 EXTINCTION

As discussed by Rieke & Low (1975), the extinction to the nucleus of NGC 253 can be estimated on the basis of the near-infrared colour of the stellar distribution, and from the depth of the silicate absorption. The 1.6–2.2-μm colour of the nucleus of NGC 253 is 0.7 mag (Becklin *et al.* 1973) which is 0.5 mag redder than that of M31 (Sandage, Becklin & Neugebauer 1969). In Section 4.6 it is shown that the 2.2-μm emission from NGC 253 is dominated by starlight, rather than by hot dust. If NGC 253 has a similar stellar distribution to M31, and if a normal extinction law applies, the visual extinction to the central stars in NGC 253 is then 7 mag. Gillett *et al.* (1975) estimated that the depth of the silicate

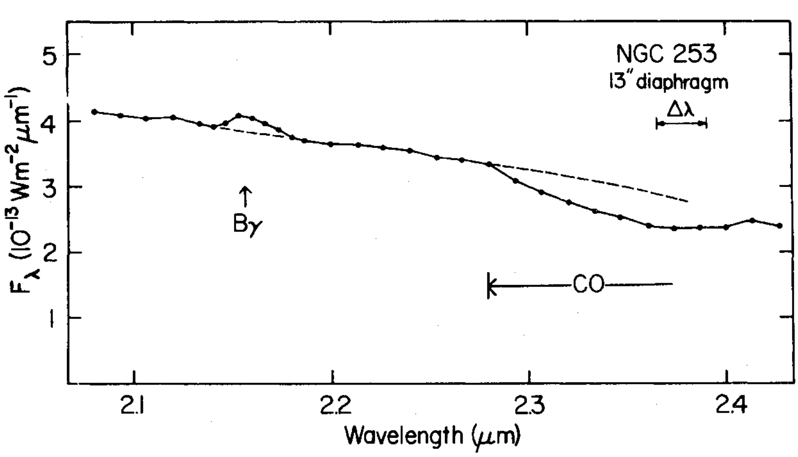

Figure 1. Spectrum of the central 13 arcsec of NGC 253 from 2.1 to 2.4 μm. The dashed lines are the estimated continuum in the absence of the CO and Brackett-γ features.

absorption feature corresponds to 15–60 mag of visual extinction. The uncertainty reflects the uncertainty in the ratio of visual to 10-μm absorption; the use of Becklin *et al.*'s (1978) ratio as measured towards the Galactic Centre would lower this estimate to a visual extinction of about 12 mag. Taken together, these methods would suggest that the visual extinction to the central region is about 10 mag, corresponding to 1 mag at 2.2 μm. If this extinction applies to the hydrogen-line emitting region, the de-reddened flux of the Brackett-γ line is $1.2 \times 10^{-15}\,\mathrm{W\,m^{-2}}$. This number will be adopted for the remainder of the paper, although it could easily be in error by a factor of 2.

4.2 IONIZATION IN THE CENTRAL REGION OF NGC 253

If the nucleus of NGC 253 behaves like a normal H II region, the rate of hydrogen ionization implied by the strength of the Brackett-γ line is $1.2 \times 10^{53}\,\mathrm{s^{-1}}$. This number is about 30 times larger than that from the central 200 pc region of our own Galaxy (Mezger & Pauls 1978); it corresponds to about 10^3 O4 stars (Panagia 1973).

The free–free radio flux density corresponding to the adopted Brackett-γ flux is calculated, using the relation given by Wynn-Williams *et al.* (1978), to be 140 mJy at 2.7 GHz. This value is a factor of 15 below that observed by Becklin *et al.* (1973) at this frequency; the non-thermal nature of the nuclear radio emission, as suggested by Rieke & Low (1975), is therefore confirmed.

The Brackett-γ line can also be used to predict the strength of the hydrogen radio recombination lines from the nucleus. If the lines are emitted in LTE at 10^4 K, the flux of the H102α line from the central 13 arcsec (150 pc) of NGC 253 would be $3.6 \times 10^{-23}\,\mathrm{W\,m^{-2}}$. Seaquist & Bell (1977), using a 4 arcmin beam, measured a flux of $1.3 \times 10^{-21}\,\mathrm{W\,m^{-2}}$ for this line. This factor of 30 discrepancy is certainly partly due to the large difference in beam size, but is very probably accentuated by stimulated emission effects of the radio line (Shaver, Churchwell & Walmsley 1978).

Ulrich (1978) measured a flux of $7 \times 10^{-16}\,\mathrm{W\,m^{-2}}$ for the Hβ line from a 20 arcsec diameter region very close to the galactic nucleus. The flux she obtained is about 6000 times larger than that predicted from the measured Brackett-γ flux density by use of Giles's (1978) calculations for a plasma at 10 000 K, and 10 mag of visual extinction. There are two possible explanations for this. The first is that the bulk of the ionized gas lies at the galactic centre, behind about 10 magnitudes of visual extinction, and that what Ulrich sees is either a foreground H II region or a small part of the central source seen through a line of low extinction. The second is that both the Hβ and the Brackett-γ fluxes refer to the same body of ionized gas, which is not associated with the nuclear regions of the galaxy and which lies behind only about 3 mag of visual extinction. The disadvantage of this latter model is that the rate of ionization for this postulated H II region, about $6 \times 10^{52}\,\mathrm{s^{-1}}$, is 80 times larger than that of the brightest galactic spiral arm H II regions such as W 49. Although there exist a few H II regions of this luminosity in M101 (Israel, Goss & Allen 1975), they are sufficiently compact that the location of such a luminous region along the line of sight to the nucleus would be particularly fortuitous.

It therefore seems reasonable to assume that the ionized gas seen at 2 μm lies at the centre of NGC 253. It is not clear how this gas is kept ionized, but the presence of large amounts of dust and of molecular clouds in NGC 253 (Rickard *et al.* 1977) makes it very plausible that the ionization arises from newly formed massive stars at the centre of the galaxy.

4.3 LATE-TYPE STARS AND THE MASS OF THE NGC 253 NUCLEUS

The presence of a strong 2.3-μm absorption feature indicates that a substantial fraction of the flux density at that wavelength arises from late-type giant or supergiant stars (Frogel *et al.* 1978). From Fig. 1, the CO index, as defined by Frogel *et al.* (1975), is 0.13 mag without a reddening correction; applying a reddening correction appropriate to NGC 253 in the manner discussed by Aaronson (1978) increases the index to about 0.2 mag. This value is among the largest found for any galaxies by Frogel *et al.* (1978), confirming that photospheric emission from late-type giants or supergiants dominates at 2.2 μm. If the extinction at 2.2 μm is 1 mag (Section 4.1) and the distance modulus is 27.7 mag, an absolute magnitude at 2.2 μm of -21.1 is obtained for the central 13 arcsec of NGC 253.

The possibility that the 2.2-μm emission from the centre of NGC 253 is dominated by M-type supergiants will be examined first. Such a possibility is suggested by the inferred presence there of a large number of O stars (Section 4.2). A comparison of the nucleus of NGC 253 with the 30 Doradus nebula in the Large Magellanic Cloud is interesting in this context, since 30 Dor is the largest well-studied H II region and is also known to be very rich in M supergiant stars (Hyland, Thomas & Robinson 1978). If the ratio of the number of M supergiants to O stars (as measured by the rate of production of ionizing photons) is the same in 30 Dor as in the nucleus of NGC 253, we may use the ionizing rate derived in Section 4.2 to predict the absolute 2.2-μm magnitude of the M supergiants in NGC 253. From the radio flux and distance of 30 Dor as given by McGee, Brooks & Batchelor (1972) and Bok (1966), with Hyland *et al.*'s (1978) list of M supergiants in 30 Dor, the absolute magnitude of the M supergiants in NGC 253 will be -16.5. Since the measured absolute magnitude of the central region of NGC 253 is -21.1, it may therefore be concluded that M supergiants cannot be responsible for the bulk of the 2.2-μm emission unless the ratio of evolved M supergiants to O stars is some 70 times larger in NGC 253 than in 30 Dor.

It therefore seems much more probable that the 2.2-μm emission arises from M giant stars rather than M supergiants, and that the late-type star population is not unlike those of other Sc galaxies. Turnrose (1976) has studied seven such galaxies, not including NGC 253, and constructed models of their stellar populations based on spectrophotometry at visible wavelengths. In all of the galaxies he studied, most of the 2.2-μm flux density comes from K and M giants, whereas most of the mass resides in the late-type dwarfs. The early-type stars, while contributing very significantly to the total luminosity, make a negligible contribution to either the mass or the 2.2-μm flux density. If, in NGC 253, the ratio of late-type giants to late-type dwarfs is similar to those in Turnrose's sample, the 2.2-μm flux density can be used to estimate the total stellar mass in the region, irrespective of the presence of the large number of O stars implied by the strength of the Brackett-γ line. Turnrose calculates the ratio of mass to visible light for all his seven Sc galaxies; these range from 0.67 to 1.52 solar units. He does not give the V–K colour for all his models, however, because of uncertainties in the appropriate choice of V–K colour to use for his M giant populations. Recently, however, Aaronson (1978) has measured the V–K colour for the central regions of five of Turnrose's galaxies, while Penston (1973) has measured it for another. The V–K colours range from 2.94 to 3.31 mag. From the six galaxies, the mean ratio of 2.2-μm flux density to the mass may be calculated and used in conjunction with the measured 2.2-μm magnitude of NGC 253 to determine a mass of $1.2 \times 10^9 M_\odot$ within its central 200 pc. This mass is comparable to the value of $2 \times 10^9 M_\odot$ estimated by Oort (1977) for the mass in the central 200 pc of the Galaxy. It is also compatible with the estimate by Combes, Gottesman & Weliachew (1977), based on 21-cm data, that NGC 253 contains $5 \times 10^9 M_\odot$ within 1 kpc of its centre.

A very much lower estimate for the mass of stars in the centre of NGC 253 was made by Ulrich (1978), who deduced from her Hα profiles that the mass within the central 20 arcsec diameter was $2 \times 10^7 M_\odot$. A possible explanation for part of the discrepancy in the nuclear mass is connected with the suggestion made above that the visible emission lines seen by

Ulrich originate at a substantial distance in front of the nucleus rather than very close to it. A measurement of the profile of the Brackett-γ line would clearly be of great interest.

4.4 THE ORIGIN OF THE FAR-INFRARED LUMINOSITY

The total far-infrared luminosity of NGC 253, as measured with a 50 arcsec beam, is $2.8 \times 10^{10} L_\odot$ (Telesco & Harper 1979). The size of this region is not known. It is of interest to examine how much of this luminosity could originate from the stars whose existence has been inferred from the 2.2-μm observations. These stars comprise two groups, the general population as seen in the 2.2-μm continuum, and the additional population of early-type stars whose presence is deduced from the existence of the strong Brackett-γ line.

To estimate the contribution from the general population of stars, the bolometric luminosity was calculated for each of Turnrose's model Sc galaxies and combined with the measured V–K colours to obtain a bolometric correction to the 2.2-μm magnitude, M_B–M_K. The mean value of this correction was +2.55, with a range of 2.14 to 2.89 mag. This correction was applied to the 2.2-μm magnitude of NGC 253 to obtain the value of $2 \times 10^9 L_\odot$ for the luminosity of the model population of stars in the central 13 arcsec of NGC 253. The fraction of this luminosity that would originate in OB stars varies from zero to 65 per cent in Turnrose's models.

On the assumption that the hydrogen giving rise to the Brackett-γ line is ionized by ultraviolet photons from O stars in environments similar to those in our own Galaxy, it is possible to estimate the luminosity contributed by this young population. Galactic H II region complexes have an approximately linear relationship between their total luminosity and their rate of ionization (Wynn-Williams & Becklin 1974). Extrapolation of Jennings' (1975) relationship to NGC 253 leads to a predicted luminosity of $8 \times 10^9 L_\odot$. It is therefore immediately evident that NGC 253 contains a more luminous young population than is predicted from Turnrose's models. Much of this luminosity arises from OB stars, but some may be from protostars, evolved stars and other objects which contribute to the heating of H II region/molecular cloud complexes.

Of the $2.8 \times 10^{10} L_\odot$ detected at far-infrared wavelengths in a 50 arcsec beam, therefore, approximately $10^{10} L_\odot$, or one-third, can be accounted for by the stars in the central 13 arcsec. It seems entirely possible that the beamsize correction could account for the remaining difference, given that both the mass, the 2.2-μm and the 10-μm flux densities (see Becklin *et al.* 1973) scale approximately as the first power of radius in this region, and that the luminosity–ionization relation for H II regions is uncertain by a factor of 2.

If the far-infrared source has a size intermediate between 13 and 50 arcsec, then, from the discussion in the previous section, it is associated with a mass in the range 1–$5 \times 10^9 M_\odot$. The bolometric mass to luminosity ratio is therefore between 0.04 and 0.2. These values are significantly higher than the value of 0.002 estimated by Rieke & Lebofsky (1978), since the latter used Ulrich's (1978) mass estimate.

4.5 NEON ABUNDANCE

Gillett *et al.* (1975) measured the [Ne II] 12.8-μm line in NGC 253, but were unable to make an accurate estimate of the neon abundance without a hydrogen line. From their flux for the neon line, the adopted Brackett-γ flux from this paper, and the formula of Petrosian (1970) a neon abundance of 1.7×10^{-4} is obtained. This value includes a factor of 2.0 for the beamsize correction from Gillett *et al.*'s 7-arcsec beam to our 13-arcsec beam. Given the various uncertainties, the calculated neon abundance agrees reasonably well with that given by Cameron (1973) for the Solar System, namely 1.1×10^{-4}. A similar result for M82 was reported by Willner *et al.* (1977).

5 Conclusions

A 2.1- to 2.4-μm spectrum of the central region of NGC 253 shows the 2.3-μm absorption feature of CO and the 2.17-μm Brackett-γ hydrogen emission line. From the strength of these features it is deduced that:

(a) The rate of ionization, and hence probably the number of OB stars, in the central 200 pc of NGC 253 is about 30 times larger than that estimated to be in the corresponding region of the Galaxy.
(b) As in other Sc galaxies, the 2.2-μm continuum emission from the central region of NGC 253 is dominated by late-type giant stars. The total mass of stars in the central 200 pc is comparable to that in the Galaxy.
(c) At least 30 per cent, and possibly all, of the luminosity emitted by dust grains at far-infrared wavelengths originates in stars whose presence is deduced from the 2.2-μm observations. Most of this luminosity is attributed to massive young stars.
(d) The total-mass to total-luminosity ratio is in the range of 0.04–0.2 solar units.
(e) There are 10 mag of visual extinction to the nucleus of NGC 253. The hydrogen emission seen at visible wavelengths probably lies significantly in front of the nucleus.
(f) The 2.7-GHz radio emission is non-thermal.

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