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The central star of the planetary nebula NGC 6302*

S.R. Pottasch[1], D. Beintema[2], F.J. Dominguez-Rodriguez[1], S. Schaeidt[3], E. Valentijn[2], and B. Vandenbussche[4,5]

[1] Kapteyn Astronomical Institute, P.O. Box 800, 9700 AV Groningen, the Netherlands
[2] SRON Laboratory for Space Research, P.O. Box 800, 9700 AV Groningen, the Netherlands
[3] Max Planck Institut für Extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
[4] ISO Science Operations Centre, Astrophysics Division of ESA, P.O. Box 50727, E-28080 Villafranca, Madrid, Spain
[5] Sterrenkundig Instituut, K.U. Leuven, Celestijnenlaan 200B, 3001 Heverlee, Belgium

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Abstract. Selected results from the ISO spectrum of NGC 6302 are reported. The intensity of the high ionization [Mg VIII] line is given. The controversy concerning the mechanism of ionization of the high ionization stages, and especially the [NeV] lines is discussed. It is concluded that all lines can be reproduced in a photoionization model, if the temperature of the central star is about 380,000 K. The abundances of several elements in the nebula is given, as well as the intensities of the lines involved.

Key words: white dwarfs, planetary nebulae: general, planetary nebulae: individual: NGC 6302

1. Introduction

The central star of the planetary nebula NGC 6302 has never been seen. This is not only because it is faint, but also because there is a dust lane running across the nebula which causes a substantial, but not complete, extinction. No star has been seen in the visual, near the center of the nebula to a magnitude of 20.4 (Gathier and Pottasch, 1989).

The fact that the central star is hot can be deduced from the spectrum. A line of Ne^{5+} was found in the IRAS LRS spectrum of this object (Pottasch et al., 1986) which requires radiation of 126 ev to form. A few years later lines of Si^{5+} and Si^{6+} were found (Ashley and Hyland, 1988). The latter ion requires 205 ev to form. In the ISO spectrum of this nebula we can confirm the presence of this line, and in addition can report on the measurement of a line of still higher ionization, the [Mg VIII] line at 3.028 microns.

The interpretation of these high stages of ionization as being caused by a hot star has been questioned. Lame and Ferland (1991) suggest that the high stages of ionization are produced by shock waves in the nebula and predict that this will heat the nebula. This theme has been taken up by Rowlands et al. (1994) who compute the electron temperature in the nebular regions where the [NeV] lines are formed. They find a value of about 70000 K and conclude that this value is much too high to be due to photoionization, and the shock wave scenario must therefore be correct. Oliva et al. (1996), on the other hand, give several arguments against shock excitation of the gas. The strongest argument is a recomputation of the electron temperature from the [NeV] lines indicating a substantially lower temperature. To obtain agreement with the values of temperature obtained from lines of ions of lower stages of ionization, these authors propose a change in the collisional cross sections for the lower levels. While this may be correct, it should be pointed out that the intensity of at least one of the [NeV] lines is observationally uncertain, and the others should be checked as well.

We present here the ISO measurements of the 14.3 and 24.3 micron measurements of [NeV] in an attempt to settle this point.

2. The observation

NGC 6302 was observed on 19 February 1996 with the SWS, using the S01 observing template (de Graauw et al., 1996). This template scans the spectrum over the full range accessible by SWS. The observation was done at the slowest rate, which reduces the spectral resolution to about half the resolution that SWS can obtain on extended sources. The data were reduced with the SWS In-

Send offprint requests to: S.R. Pottasch

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teractive Analysis software, using the Pipeline V4.3 modules. The wavelength calibration (Valentijn et al., 1996) and the flux calibration (Schaeidt et al., 1996) were based on the calibration files adopted as a standard for this issue of A&A Letters.

3. The [Mg VIII] and the [Si IX] lines

Fig. 1 shows the ISO spectrum of NGC 6302 in the region of 3.03 microns. [Mg VIII] is the strongest line in this region and has a wavelength of 3.02749±0.00035 microns. There can be little doubt of its reality. The line is also seen in the spectrum of Reconditi and Oliva (1993).The intensity of this line was measured to be 3×10^{-12} erg cm^{-2} s^{-1}. This intensity must be corrected for extinction, which is discussed in the following section. Using a normal extinction law, this correction amounts to about 20%. There are a number of hydrogen lines observed in this part of the spectrum and we have checked whether these lines agree in intensity with what is expected on the basis of the theoretical spectrum (Hummer and Storey, 1987) for$T_e = 20$ 000K and $N_e = 10^4$ cm^{-3} and the total radio continuum emission at 6 cm (Gomez et al., 1993). The $Pf\alpha$ line at 7.460 μm, with an intensity of about 9×10^{-12} erg cm^{-2} s-1, agrees very well with the expectation. The other H lines, including $Br\alpha$ and $Br\beta$, are too weak, by a factor of 2 to 2.5. This may be only partly due to extinction, because the total $Br\gamma$ line measured by Ashley and Hyland (1988) from the ground is higher than would be expected from an extrapolation of the ISO results. New measurements with ISO will be taken to further investigate this problem; for the present we warn that the line intensities in this measurement of NGC 6302 in the range 2.4 to 5 μm may be too low by the factor to 2.5.

The [Si IX] line at 3.935 microns is more uncertain. This part of the spectrum is also shown in the figure. Oliva et al. (1996) do not detect the line to a level of 2×10^{-13} erg cm^{-2} s^{-1}. Our spectra, taken at face value, would give a somewhat higher intensity, but new measurements should be made to check the reality of this line.

4. Extinction to NGC 6302

For a complete discussion of the NeV spectrum it is necessary to include the line at 3426$\AA$. The intensity of this line has been measured by Rowlands et al.(1994) with a diaphragm of 27″ diameter, which essentially covers the entire nebula as seen in radio continuum emission. The intensity measured, 1.92×10^{-11} erg cm^{-2} s^{-1}, must be corrected for extinction. The correction must be carefully done, because part of the extinction is local and thus may vary over the nebula.

There are various ways of determining the extinction. The first is by comparing the radio continuum emission at 6cm with the Hβ flux. The total radio emission is 3100 mJy (Zijlstra et al., 1989) and the total Hβ flux is

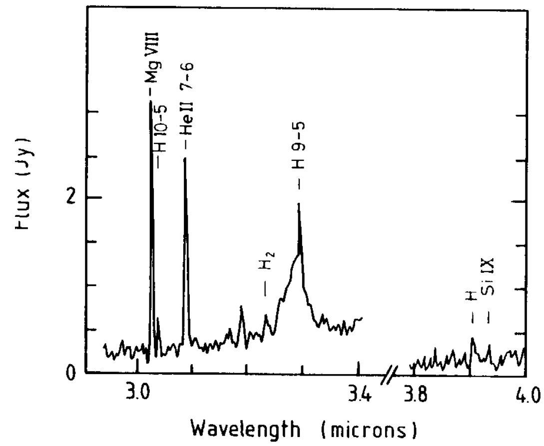

Fig. 1. A portion of the SWS spectrum between 3 and 4 microns. The [Mg VIII] is clearly seen at 3.027 microns. The possible [Si IX] at 3.935 microns line is also indicated. The continuum levels are uncertain, and the apparent drop between 3.4 and 3.8 μm has no meaning.

2.95×10^{-11}erg cm^{-2} s^{-1} (Copetti, 1990). Using a singly ionized helium to hydrogen ratio of 0.12, a doubly ionized helium to hydrogen ratio of 0.08 and an electron temperature of 20000 K, an average extinction of E_{b-v}=0.865 is found. This is an average extinction over the entire nebula, strongly weighted to the central portions. An extinction may also be found from a comparison of the Pfund 6-5 line at 7.46 microns with the Hβ line. This gives a similar extinction, which is shown in Table 1. The intensities of the HeII lines seen in the IUE spectrum of Aller et al. (1981) can also be used to determine extinction. These values refer to the 10″ × 20″ region at the center of the nebula. Finally the ratio of the two HeII lines seen in the ground based spectrum of Aller et al. (1981) can be used. The slit position for this measurement is not specified but it presumably refers to a brighter region not far from the center. All values of extinction are summarized in Table 1, and are very similar: because of this the average value will be used (E_{b-v}=0.855).

Table 1. Extinction Determination

METHOD	REGION	E_{B-V}
6cm Radio/Hβ	whole nebula	0.865
Hβ/Pfund α	whole nebula	0.835
HeII 1640/3203	10″ × 20″	0.88
HeII 1640/2734	10″ × 20″	0.856
HeII 3203/4686	bright patch	0.840

5. The [NeV] intensities

The observed values of the NeV line intensities are shown in Table 2. The line at 24.3 microns was observed both by ISO, with a diaphragm of about $14'' \times 20''$ and by the KAO (Rowlands et al., 1994) with a diaphragm of $27''$. The intensities in both cases are very similar. The ultraviolet line at 3426 Å was observed by the same authors with the same diaphragm. The previous measurement of the 14.3 micron line was made by the IRAS LRS (Pottasch et al., 1986). It refers to the entire nebula. Even though it is a lower value than the ISO result, its uncertainty is much larger. In the following analysis, the ISO intensities will be used, together with the value of the ultraviolet line measured by Rowlands et al. This must be corrected for the extinction given above, which amounts to a factor of 49.3. The extinction corrected intensity of this line is thus 95×10^{-11} erg cm^{-2} s^{-1}. The accuracy of the line intensities given in Tables 2 and 3 is expected to be better than 30%.

Table 2. [NeV] Line Intensities(10^{-11}erg cm^{-2} s^{-1})

LINE	ISO	OTHER	REF.
24.31 μm	28.0	32.3	(1) KAO
14.32 μm	70.0	49	(2) IRAS LRS
3426 Å		1.92	(1)

References: (1) Rowlands et al., 1994,
(2) Pottasch et al. 1986

These intensities can be used to determine what the electron temperature and density would be in a region in which these quantities were constant. The result is shown in Fig. 2: T_e=21000 K and n_e=1.8 $\times 10^4$ cm^{-3}. These values are typical of the values found for this nebula from other diagnostic line ratios (see Oliva et al., 1996, for a summary). This indicates that the [NeV] lines are formed in the same photoionized region as the rest of the spectrum. One is therefore justified in using photoionization models to fix the temperature of the central star.

6. The temperature of the central star

Photoionization models for this nebula have been made using the "Cloudy" program. A spherically symmetric, constant density case was considered. The line intensities used in the modelling were all taken from the ISO measurements, except that the ultraviolet NeV line discussed above was also included. The ISO measurements are extensive enough so that the following ions could be included: Ne^{+}, Ne^{2+}, Ne^{4+}, Ne^{5+}, Ar^{+}, Ar^{2+}, Ar^{4+}, Mg^{3+}, Mg^{4+}, Mg^{7+}. The intensities of most of these lines are specified in Tables 2 and 3.

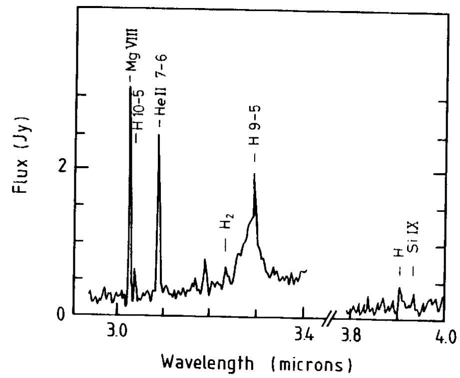

Fig. 2. Diagnostic diagram for the NeV line ratio. The two curves are labelled by the line intensity ratio which are used in deriving them. The collision cross-sections used are from Lennon and Burke (1991).

It was assumed that the star radiates as a blackbody. While it is not clear how good such an approximation is, the observed spectrum could be reproduced within about 50% by a range of models. In these models the temperature of the star could vary between 350000 and 400000 K.

This temperature is somewhat lower than obtained by Ashley and Hyland (1988) in spite of the use of the [Mg VIII] line which has a higher ionization potential than the [Si VII] line which they use. We can reproduce this line intensity as well with our model with a lower stellar temperature. Our temperature is consistent with the temperature found from the Energy Balance method: 350,000K (Preite-Martinez and Pottasch, 1983).

7. Abundances

In Table 3 intensities of selected lines of four elements are listed. Not all the lines of these elements are given, but these were used in the analysis since their intensities are the most reliable. The abundances are found from the same analysis described above, and are given in Table 4. The abundances are somewhat lower than found by Aller et al., (1981), sometimes by almost a factor 2. The magnesium abundance is reported for the first time in NGC 6302. It is about a factor 2 higher than in NGC 7027 (Beintema et al., this issue).

8. Discussion

For this discussion, it is useful to include the distance to NGC 6302. A determination from the angular expansion measured using VLA data taken at two epochs separated by 2.75 years, gives the most reliable result to date (Gomez et al., 1993). They find a value of 1.6±0.6 Kpc. An upper limit to the distance can also be found by comparing line or radio continuum emission to either extragalactic systems or the galactic bulge. Since no galactic bulge PN are

Table 3. Selected Line Intensities in NGC 6302

ION	WAVELENGTH microns	INTENSITY 10^{-12} erg cm^{-2}s^{-1}
[Ne II]	12.808	130
[Ne III]	15.550	290
[NeIII]	36.001	27
[NeVI]	7.650	630
[ArII]	6.983	39
[ArV]	13.097	29
[MgV]	5.608	39
[MgVII]	5.502	30
[MgVIII]	3.027	3 to 6
[NaIII]	7.315	5.5
[NaVI]	8.608	11

Table 4. Selected Abundances in NGC 6302

ELEMENT	$log[X/H]$	
Ne	7.86	7.99
Mg	7.08	
Ar	6.70	6.93
Na	6.30	6.57
	This paper	Aller et al. (1981)

found with a 6 cm. flux density greater than 90 mJy (Pottasch, 1990), this would lead to the conclusion that NGC 6302 is closer than 1.3 Kpc (assuming that the galactic bulge is at 7.5 Kpc). The similarity of these values indicates that NGC 6302 is one of the very brightest PN in the galaxy. In the remainder of this paper we will use the value of $d = 1.6 Kpc$.

The total IRAS infrared luminosity at that distance is 7.0×10^3 L⊙. In addition the sum of all visible, infrared and ultraviolet line emission (longward of 912$\AA$) is about 3.9×10^3 L⊙ (Preite-Martinez and Pottasch, 1983 coupled with the unreddened $H\beta$ flux given above). The total luminosity is about 1.1×10^4 L⊙. If the (blackbody) temperature is 3.8×10^5 K, then the radius is 2.5×10^{-2} R⊙. If the mass is assumed to be 0.9 M⊙, the gravity is 9.1×10^7 cm s^{-2}, or $log\ g = 7.96$. These values are typical of what is expected from a white dwarf, or a star approaching very closely to the white dwarf stage. This lends some credence to the blackbody assumption.

It is interesting to try to compare the above values with theoretical tracks for central stars in the H-R diagram. For this purpose we have used the tracks recently computed by Blocker (1995), who also uses blackbodies to model the central star. Blocker shows several tracks which extend to temperatures as high, or higher, than T = 3.8 $\times 10^5$ K. They all have masses of 0.84 M⊙ or higher. But the luminosity is at least a factor of 2 higher than found here. Furthermore the time scale from the AGB to the higher temperature is 200 years or less. From the model of the radio emission given by Gomez et al. (1993), NGC 6302 has an "outer" radius of 5$''$.3, corresponding to about 10^{17}cm. With the expansion velocity they give of 13 km s^{-1}, the nebula is 2500 years old. This is considerably higher than the calculated tracks predict.

The temperature and radius found above allow us to predict the visual magnitude of the star. Without allowing for extinction, it should be $V_o = 17.6$ mag. This value is independent of the distance. It does depend on the assumption of blackbody radiation. A direct measurement of the magnitude will therefore provide evidence concerning the model for the flux distribution from the central star. It is a difficult measurement, since in all probability the central star lies behind the dust lane going through the center of the PN, which might have 5 magnitudes of extinction. One could also think of measuring the star at 2.2 microns. The K magnitude is about 18 and the extinction is considerably lower than in the visual. However this is still quite faint, while the nebular background is quite bright in the infrared.

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