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IONIZED MAGNESIUM IN THE PLANETARY NEBULA NGC 7027

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ABSTRACT

Observations of NGC 7027 are presented for six ionic lines: Mg^{+3} (4.48 μm), Mg^{+4} (5.61 μm), H° (4.05 and 7.46 μm), Ne^{+5} (7.64 μm), and Ar^{+5} (4.53 μm). The magnesium lines are consistent with the measurements of Russell, Soifer, and Willner, and the hydrogen lines are consistent with the line strengths predicted from the radio flux. Upper limits were obtained for the neon and argon lines. The abundance of magnesium in the central part of the nebula is highly uncertain because the fine-structure collision strengths are poorly known. The strong gradient of magnesium abundance from the inner to the outer portions of the nebula derived by Péquignot and Stasinska could be an artifact of this uncertainty. A brief analysis of the effective stellar temperature derived from the magnesium line ratios is given.

Subject headings: nebulae: abundances — nebulae: individual — nebulae: planetary

I. INTRODUCTION

NGC 7027 is a compact, high-excitation planetary nebula noted for its brightness at optical and infrared wavelengths. Because it is bright, many observations have been made of this nebula, and there are several models of the nebula which correctly predict the strengths of many (but not all) of the emission lines (e.g., Shields 1978; Péquignot, Aldrovandi, and Stasinska 1978). One feature the models cannot explain is the relatively low abundance of singly ionized magnesium compared with the more highly ionized states (principally Mg^{+3} and Mg^{+4}). Péquignot and Stasinska (1980, hereafter PS) derive a strong gradient in the gaseous magnesium abundance based on the observations of Russell, Soifer, and Willner (1977, hereafter RSW), so Mg has a normal abundance in the center of the nebula (where it is highly ionized) and is depleted in the outer parts by about a factor of 10. This abundance gradient is difficult to produce in static models of the nebula assuming normal ionization and recombination processes. PS favor magnesium depletion in dust grains with subsequent selective destruction of the grains near to the center of the nebula by radiation in the early stages of nebular evolution.

The abundance gradient is inferred from a comparison of two blended lines of Mg^{+} near 2800 Å, three lines of Mg^{+4} at 2783 and 2928 Å and at 5.61 μm, and a line of Mg^{+3} at 4.48 μm. The infrared lines were observed by RSW and were only tentatively identified with the magnesium ions owing mainly to the low resolution of the spectra. In fact, RSW were unable to separate the Mg^{+3} line from a nearby line of Ar^{+5} at 4.48 μm. We have observed NGC 7027 with sufficient spectral resolution to isolate the infrared fine-structure transitions of these ions and uniquely identify the lines. In the following sections, we discuss the observations, derivation of abundances, and the color temperature of the central star as determined from the relative line intensities.

II. OBSERVATIONS

The observations were made from the Kuiper Airborne Observatory in 1981 June with the cooled grating spectrometer described by Beckwith *et al.* (1983). The spectral resolving power ($\lambda/\Delta\lambda$) was approximately 800. The focal plane diaphragm subtended a 28″ diameter circle on the sky, and the secondary mirror was chopped 60″ at 15 Hz to subtract sky and telescope background.

Measurements of a low-pressure argon lamp were made in flight to calibrate the wavelength scale. The flux density scale was calibrated by measurements of α Bootes, and we estimate an overall uncertainty of 10% in this scale; as noted in the next section, the measured flux of the Bα line is within 10% of the value predicted from the radio continuum measurements of Terzian (1978). Spectra of the Moon were taken to determine the extent of telluric absorption near the nebular lines of interest. Because the spectral resolution is inadequate to resolve some of the individual telluric lines that could interfere with nebular lines, we cannot be certain the nebular lines are completely free of narrow telluric features.

III. RESULTS

The spectra of the $2p^5\ ^2P_{3/2} \rightarrow {}^2P_{1/2}$ line of Mg^{+3} (4.48 μm) and the $2p^4\ ^3P_2 \rightarrow {}^3P_1$ line of Mg^{+4} (5.61 μm) are shown in Figure 1. Because the lines are not resolved at this resolution, the spectra have been fitted with an instrumental profile function to determine the fluxes and uncertainties. Spectra were also taken of the Brα (4.05 μm) and Pfα (7.46 μm) lines of H° and of the $3p^1\ ^2P_{1/2} \rightarrow {}^2P_{3/2}$ line of Ar^{+5} (4.53 μm) and the $2p^1\ ^2P_{1/2} \rightarrow {}^2P_{3/2}$ line of Ne^{+5} (7.64 μm); we obtained only upper limits for the latter two lines.

Table 1 gives the observed fluxes or limits for the lines described above. The flux of the 5.61 μm Mg^{+4} line agrees very well with the value found by RSW. The telluric absorption near 5.61 μm is small as seen in our spectra of the Moon and as predicted from computations of the telluric absorption

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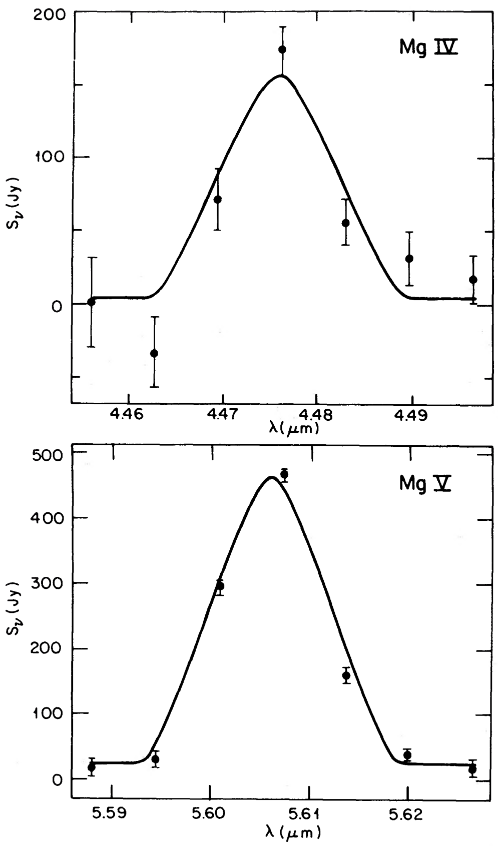

FIG. 1.—Measurement of the Mg IV and Mg V lines are shown. The solid lines represent the best fits of the instrumental profile function to line strengths as discussed in the text.

made at the Aerospace Corporation by A. Kishi using the AFGL FASCODE (see also Augason and Burns 1977). The flux of the Mg^{+3} line at 4.5 μm is quite likely affected by telluric absorption which has not been removed by our calibration procedure. RSW observed two different fluxes for this line (1.9×10^{-13} and 4.3×10^{-13} W m^{-2}) at different dates, and the new measurement is intermediate between these two values. The computer calculations show several strong telluric lines very close to the Mg^{+3} line. The telluric absorption will decrease the observed line flux somewhat, and the flux given in Table 1 may be too small, but we think the error is probably less than a factor of 2.

TABLE 1

OBSERVED LINE FLUXES

Line	λ_0 (μm)	$F(10^{-14}$ W $m^{-2})$	Observed λ (μm)
Brα ($n = 5 \rightarrow 4$)..............	4.0512	16.3 ± 2.2	4.0508 ± 0.004
Pfα ($n = 6 \rightarrow 5$)	7.457	5.6 ± 1.5	7.4623 ± 0.02
Mg^{+3} ($2p^5\ ^2P_{3/2} \rightarrow {}^2P_{1/2}$)......	4.488	31 ± 3	4.4761 ± 0.008
Mg^{+4} ($2p^4\ ^3P_1 \rightarrow {}^3P_2$)	5.608	56.0 ± 6	5.6063 ± 0.01
Ar^{+5} ($3p^1\ ^2P_{1/2} \rightarrow {}^2P_{3/2}$)......	4.53	<2	...
Ne^{+5} ($2p^1\ ^2P_{1/2} \rightarrow {}^2P_{3/2}$)......	7.642	<5.4	...

It is clear from the new observations that the feature observed by RSW at 4.5 μm was the Mg^{+3} line only with no contribution to the total flux from the Ar^{+5} line. In the following sections, we compare the observed line strengths to those expected from models for the nebula and other observations.

IV. DISCUSSION

a) Hydrogen Recombination Lines

The intensity of the Brα line agrees well with that predicted from the radio continuum measurements of the free-free flux density. Assuming an electron temperature of 13,000 K and density of 10^5 cm^{-3} (Perinotto, Panagia, and Benvenuti 1980) and case B recombination theory (Brocklehurst 1971; Osterbrock 1974; Giles 1977), the flux in the Brα line is:

$$F(\mathrm{Br}\alpha) = 2.16 \times 10^{-14} F(5\ \mathrm{GHz})\ \mathrm{W\ m^{-2}}\,, \qquad (1)$$

where F(5 GHz) is the radio continuum flux density in Jy. Using Terzian's (1978) value of 6.4 Jy for F(5 GHz) and correcting for 25% self-absorption (cf. Perinotto, Panagia, and Benvenuti 1980), the predicted Brα flux is 1.7×10^{-13} W m^{-2}, which agrees with the observed value of 1.6×10^{-13} W m^{-2} within the uncertainties. The correction for interstellar extinction at 4.05 μm is smaller than the measurement uncertainty in this case (Treffers *et al.* 1976), but the correction would cause the observed and predicted fluxes to agree even better.

The ratio of Pfα to Brα also agrees with the value predicted by case B recombination theory, although the uncertainty is large. The observed flux ratio is $F(\mathrm{Pf}\alpha)/F(\mathrm{Br}\alpha) = 0.34 \pm 0.10$, whereas the predicted ratio is 0.33.

b) Magnesium Abundance

To calculate the ionic abundances, we solved the statistical equilibrium equations for the populations of the five lowest levels of Mg^{+4} and the two lowest levels of Mg^{+3} assuming only collisional and spontaneous radiative transitions. With the collision strengths given by Saraph, Seaton, and Shemming (1969), the transition rates given by Wiese, Smith, and Miles (1969), and the temperature and density given above, the line fluxes imply the following abundances:

$$N(\mathrm{Mg}^{+3}) = (0.9 \pm 0.1) \times 10^{-5}$$

and

$$N(\mathrm{Mg}^{+4}) = (1.6 \pm 0.1) \times 10^{-5}\,,$$

where $N(A)$ represents the abundance of A relative to hydrogen. These are average values for the nebula. The derived abundances depend only weakly on the temperature and density used in the calculations. A lower limit to the total magnesium abundance is:

$$N(\mathrm{Mg}) \geq 2.5 \times 10^{-5}\,.$$

In solving the statistical equilibrium equations, it became evident that the uncertainties in the derived abundances depend mainly on the uncertainties in the collision strengths of Saraph, Seaton, and Shemming (1969); the radiative transition rates are fairly well known, and their uncertainties do not figure strongly into the abundance estimates. The derived abundance of Mg^{+3} depends almost inversely on the collision strength

TABLE 2

IONIZATION ENERGIES

Ion	Energy to Ionize (eV)	Wavelength (Å)
Mg^0	7.65	1621
Mg^+	15.0	825
Mg^{++}	80.1	155
Mg^{+3}	109.3	113
Mg^{+4}	141.3	88
H^0	13.6	912
He^0	24.6	504
He^+	54.4	228

between $^2P_{3/2}$ and $^2P_{1/2}$ levels, which we took to be 0.31. The derived abundance of Mg^{+4} depends almost inversely on the collision strength between the $^3P_2$ and $^3P_1$ levels, which we took to be 0.39; the other collision strengths are not very important for the level populations. Since these collision strengths are not well known, the abundance estimates are uncertain with the uncertainty being approximately proportional to the uncertainty in the collision strengths.

Some of the collision strengths for other ions have been recalculated with occasional large changes in the values. Factors of 2–3 appear to be typical with some strengths changing by as much as a factor of 10 (Mendoza 1983). The most recent calculations include resonances that were not treated by Saraph, Seaton, and Shemming (1969), so the new collision strengths are larger than the early ones. Therefore, the abundances estimated here may be too large by factors of 3–10.

Putting aside the uncertainty in collision strengths for the moment, the average magnesium abundance derived above is still somewhat misleading. The Mg^{+3} and Mg^{+4} ions are produced mainly in the center of the nebula, whereas the hydrogen recombination lines are produced throughout the ionized region. Table 2 gives the energies needed to ionize different species of magnesium, with hydrogen and helium included for comparison. To estimate the true magnesium abundance from the relative line strengths of magnesium and hydrogen, we used a model for the nebula kindly made available to us by G. Shields. The original model is described by Shields (1978) and has been revised to include the effects of charge exchange reactions.

Using the stellar atmosphere of Hummer and Mihalas (1970) for an effective temperature of 166,000 K and log $g = 7.0$, this model gave a good fit to the intensities of the optical lines, but it was unable to reproduce the observed ratio of Mg^{+4} to Mg^{+3}; the predicted ratio was 0.73 compared to the observed ratio of 1.8 ± 0.4. Without Mg charge exchange reactions, the model predicted a ratio of 1.4 for the two lines, in better agreement with the observed value. However, the uncertainties in the abundance ratio introduced by uncertainties in the collision strengths and telluric absorption are sufficiently severe that we cannot rule out the importance of charge exchange (Butler and Dalgarno 1980).

We used the model to assess the fraction of total Mg which is in the form of Mg^{+3} and Mg^{+4}. The calculations indicate the fraction is never larger than 0.24, regardless of whether charge exchange is included. The most abundant species are Mg^{+5} in the inner part of the nebula, Mg^{++} in the middle part, and Mg^+ in the outermost part (the neutral hydrogen zone). Since the ionization edge for Mg^{+4} is at 88 Å, shortward of the shortest absorption edge in the Hummer and Mihalas atmospheres, neglect of the Mg^{+4} edge and a nearby O^{+5} edge may cause the model to overestimate the abundance of Mg^{+5}. If we include all the Mg^{+5} in the models with Mg^{+4} and Mg^{+3}, the fraction in those forms is as much as 0.5. Even using this extreme correction factor, the total Mg abundance is $8\text{–}15 \times 10^{-5}$, at least twice the solar abundance.

Several factors contribute to the uncertainty in this final abundance, the major factor being the uncertainty in the collision strengths for the fine-structure levels of the magnesium ions. If we assume the extreme case for the collision strength uncertainty, it is possible to lower the abundance by a factor of 10, making the magnesium abundance in the inner part of the nebula about one-fifth the solar abundance. There would then be a very slight abundance gradient between the inner and outer parts of the nebula, but considerably less than derived by PS. On the other hand, if the Mg^{+3} line is too weak by a factor of 2 (from telluric interference), the collision strengths are only a factor of 2 too small, and the larger abundance implied by the model calculations is applicable, then the abundance in the inner part of the nebula could still be twice the solar value making the abundance gradient even stronger than supposed by PS. Considering the uncertainties in these derivations, we feel the evidence for a strong magnesium abundance gradient is not compelling, and further progress must await new calculations of the ionic collision strengths.

c) *The Stellar Temperature*

Mg^{+4} is one of the most highly ionized species observed in the nebula. The energy required to produce Mg^{+4} from Mg^{+3} is 109 eV (cf. Table 2), and the presence of Mg^{+4} can be used to place at least a lower limit on the temperature of the central star. Shield's nebular model with a blackbody stellar atmosphere at 150,000 K reproduces the Mg^{+3} ratio of the Mg^{+3} to Mg^{+4} lines fairly well. PS used a slightly different model with a stellar temperature of 170,000 K to produce the line ratios. The temperature implied by these data are all quite high.

It is often useful to derive stellar temperatures using a simple analytical approximation for the line ratios rather than a nebular model. Such an approximation is discussed by Natta, Pottasch, and Preite-Martinez (1980) for the abundance ratio of a pair of ions in the case of static photoionizations. We used the approximation for the two ions in question to derive stellar temperature of 105,000 K. Unfortunately, the analytical approximation is almost certainly in error for this case. The assumptions needed to make the approximation (for example, that ions confined to sharp Strömgren spheres) are almost certainly not valid for magnesium in NGC 7027. The nebular models are important, in this case, to make quantitative predictions from the observed line strengths.

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REFERENCES

Augason, G. C., and Burns, N. S. 1977, NASA Technical Memorandum TM X-73, p. 194.
Beckwith, S., Evans, N. J., II, Gatley, I., Gull, G., and Russell, R. W. 1983, *Ap. J.*, **264**, 152.
Brocklehurst, M. 1971, *M.N.R.A.S.*, **153**, 471.
Butler, S. E., and Dalgarno, A. 1980, *Ap. J.*, **241**, 838.
Giles, K. 1977, *M.N.R.A.S.*, **180**, 57P.
Hummer, D. G., and Mihalas, D. 1970, *M.N.R.A.S.*, **147**, 339.
Mendoza, C. 1983, in *IAU Symposium 103, Planetary Nebulae*, ed. D. H. Flower (Dordrecht: Reidel), p. 143.
Natta, A., Pottasch, S. R., and Preite-Martinez, A. 1980, *Astr. Ap.*, **84**, 284.
Osterbrock, D. E. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: W. H. Freeman and Company).
Péquignot, D., Aldrovandi, S. M. V., and Stasinska, G. 1983, *Astr. Ap.*, **63**, 313.
Péquignot, D., and Stasinska, G. 1980, *Astr. Ap.*, **81**, 121 (PS).
Perinotto, M., Panagia, N., and Benvenuti, P. 1980, *Astr. Ap.*, **85**, 332.
Russell, R. W., Soifer, B. T., and Willner, S. P. 1977, *Ap. J.* (*Letters*), **217**, L149 (RSW).
Saraph, H. E., Seaton, M. J., and Shemming, J. 1969, *Phil. Trans. Roy. Soc. London*, *A*, **264**, 77.
Shields, G. 1978, *Ap. J.*, **219**, 565.
Terzian, Y. 1978, in *IAU Symposium 76, Planetary Nebulae Observations and Theory*, ed. Y. Terzian (Dordrecht: Reidel), p. 111.
Treffers, R. R., Fink, U., Larson, H. P., and Gautier, T. N., III. 1976, *Ap. J.*, **209**, 793.
Wiese, W. L., Smith, M. W., and Miles, B. M. 1969, *Atomic Transition Probabilities*, Vol. **2**, NSRDS-NBS4.

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