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DETECTION OF THE [Ne III] 36 MICRON LINE IN THE PLANETARY NEBULA NGC 6543

M. A. SHURE, J. R. HOUCK, AND G. E. GULL
Center for Radiophysics and Space Research, Cornell University
AND
T. HERTER
Grumman Aerospace Corporation, Bethpage, New York
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ABSTRACT

We present the first observation of the [Ne III] 36.02 μm line in a planetary nebula—NGC 6543. Since the dominant form of neon in medium-excitation to high-excitation planetary nebulae is Ne III, the abundance of this ion is important in determining the total neon abundance. Use of the 36 μm line for an abundance determination has the advantage of insensitivity to temperature uncertainties. However, current atomic parameters lead to a Ne III abundance in NGC 6543 which is 4.5 times the cosmic neon abundance and 2.6 times the abundance from optical line studies. Although such a high abundance cannot be ruled out immediately, inaccuracies in the infrared level collision strengths are suspected because resonances were neglected in their calculation. The 36 μm line is also useful as a temperature probe when combined with the [Ne III] 3868 Å line. When compared to [Ne III] 15.56 μm fluxes, a temperature-insensitive density estimate may be obtained. The utility of these line ratios depends upon the actual infrared level collision strengths, which will affect the density range over which they are sensitive.

Subject headings: infrared: spectra — nebulae: abundances — nebulae: planetary

I. INTRODUCTION

In most medium-excitation to high-excitation planetary nebulae, neon is predominantly twice-ionized (see, e.g., Aller and Czyzak 1983). In neon abundance studies of planetaries, therefore, an important probe has been the brightest optical line of Ne III, located at 3868 Å.

Ne III abundances derived from the 3868 Å and Hβ lines are unfortunately affected by the strong temperature dependence of the emissivity. An uncertainty in nebular temperature of ±1000 K at 8000 K may lead to an error as large as a factor of 3.6 in the abundance. Spatial variations of temperature in the Ne III regions translate into similar uncertainties in an abundance derived assuming a single temperature.

The infrared fine-structure lines of Ne III at 15.56 and 36.02 μm (see Fig. 1) are not temperature sensitive. Their use in abundance studies would therefore alleviate this problem with the analysis of optical line data. Because of attenuation by atmospheric CO_2, the 15 μm line is not observable even from airborne altitudes. On the other hand, the 36 μm line is observable from aircraft, although it is in the wing of a pressure-broadened H_2O line. Erickson *et al.* (1983) have made a possible detection of the 36 μm line in the H II region M17. We present the first detection of this line in a planetary nebula —NGC 6543.

If the extinction correction for an object is well known, the infrared to 3868 Å line ratio can be used to obtain a nebular temperature. In addition, when 15 μm fluxes from spaceborne telescopes such as the *Infrared Astronomical Satellite* (*IRAS*) or the Shuttle Infrared Telescope Facility (SIRTF) become available, the ratio of the two infrared lines can be used to derive a temperature-insensitive estimate of nebular densities.

II. OBSERVATIONS

The 36.02 μm line was observed using the liquid-helium-cooled high-resolution grating spectrometer described by Houck and Gull (1982). The instrument was used on the 91 cm telescope of NASA's Kuiper Airborne Observatory (KAO).

The Ne III line was observed from the KAO on the night of 1983 July 20. The spectrum is shown in Figure 2. The line is not resolved so that the FWHM of the line profile is the same as the instrumental response width, 0.06 μm. The line position is 36.02 ± 0.01 μm (all errors quoted in this *Letter* are 1 σ). This is in the pressure-broadened wing of an H_2O line at 35.938 μm. The usual procedure for calibrating a spectrum is to divide by a spectrum of the Moon measured on the same flight, which should suffer the same attenuation by atmospheric lines. However, after convolving the actual lunar spectrum with the instrumental profile to obtain the observed lunar spectrum, the observed transmission at the Ne III line in the H_2O line wing will be lower than the actual transmission at this wavelength. We used high-resolution atmospheric model line spectra to correct for this effect. By comparing the convolved (instrumental response with model spectrum) to the model transmission at the Ne III line, we obtained a correction to the observed line flux of 15%. The model transmission at 36.02 μm is 0.78. After calibrating the NGC 6543 spectrum with the lunar spectrum and including the convolution correction, the Ne III line was fitted with a Gaussian instrumental

1984ApJ...281L..29S

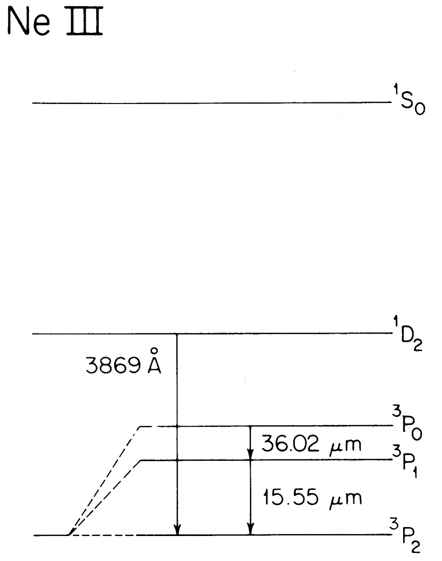

FIG. 1.—Energy levels of the Ne III ion. Level spacings are to scale, with the scale for ^3P levels expanded.

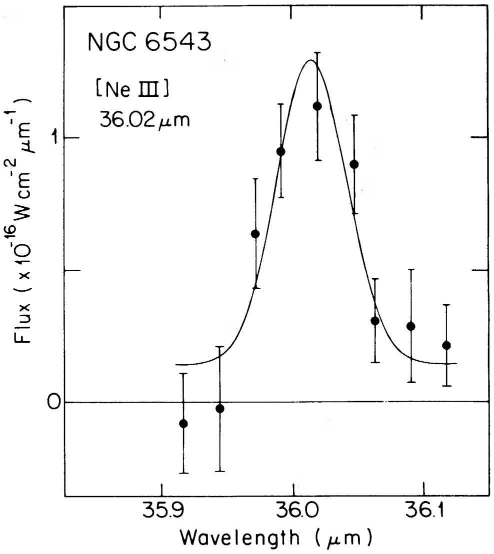

FIG. 2.—Calibrated spectrum of NGC 6543 centered on the [Ne III] 36.02 μm line.

profile (see Fig. 2). The resulting line flux is $(7.7 \pm 1.3) \times 10^{-18}$ W cm^{-2}.

The diameter of our circular beam was 30″. The [O III] 4959 + 5007 Å map of NGC 6543 made by Phillips, Reay, and Worswick (1977) is roughly oval with dimensions of 17″ × 23″ (FWHM). Since Munch (1968) found that the [Ne III] 3868 Å and [O III] images were very similar in appearance, the Ne III–emitting regions of the nebula should have been entirely within our beam.

III. IONIC ABUNDANCE AND TEMPERATURE

By combining the above Ne III flux with the optically thin, free-free flux from the nebula, an ionic abundance can be calculated (cf. Herter *et al.* 1981). We have assumed an effective positive ion density of 1.16 times the hydrogen density. The radio flux at 10.63 GHz is 0.77 ± 0.08 Jy (Higgs 1971). We assume an electron density of 4000 cm^{-3} which is an average from [O II] and [Cl III] density contour maps of Dopita and Gibbons (1975). From the optical line O III temperature map of Reay and Worswick (1982), we obtain an average temperature of 8000 K (the contours range from 7750 to 9000 K). Collision strengths and transition probabilities from Saraph, Seaton, and Shemming (1969) and Pradhan (1974) were used to set up the atomic level rate equations from which populations and line emissivities were calculated. The resulting ionic abundance of Ne III relative to hydrogen is $(3.7 \pm 0.7) \times 10^{-4}$. Since the total cosmic abundance of neon is 8.3×10^{-5} (Allen 1981), the derived total neon abundance in NGC 6543 is at least 4.5 times the cosmic abundance. On the other hand, the Ne III abundance derived from the [Ne III] 3868 Å to Hβ line ratio is 1.4×10^{-4} (Aller and Czyzak 1983), only 1.7 times cosmic neon abundance.

Two possible explanations for this infrared versus optical abundance discrepancy (a factor of 2.6) are a temperature overestimate for the optical line analysis or incorrect atomic parameters used for the optical or IR abundances, or for both. In analyzing the optical line intensities, Aller and Czyzak (1983) assumed a temperature of 8000 K. The optical abundance depends on assumed temperature as $T^{-0.4} \exp(-37{,}230\ \mathrm{K}/T)$ (see, e.g., Osterbrock 1974). At 8000 K, this may be fitted by a power law of the form $T^{-5.2}$. The optical result could be made to agree with the infrared determination by assuming a temperature of approximately 6700 K. Since the O III temperature contours on the map of Reay and Worswick (1982) range from 7750 to 9000 K, a temperature of 6700 K seems unlikely. Because of the insensitivity to temperature of the infrared line and free-free radio emission, the infrared abundance is quite insensitive to assumed temperature, varying as $T^{0.15}$ for densities less than the collisional critical density (42,000 cm^{-3} for the 36 μm line). At higher densities, the abundance varies as $T^{-0.35}$.

Another possible explanation for the abundance discrepancy is that one or more of the atomic parameters used in deriving abundances is incorrect. According to Mendoza (1983), the transition probabilities for Ne III are quite accurately known. Moreover, he notes that the calculated collision strengths between the ^3P, ^1D, and ^1S multiplets (Pradhan 1974) are probably fairly accurate. Thus, the optical level parameters are probably correct. However, the most recent collision strengths for transitions within the inverted ^3P multiplet which are responsible for the infrared lines (Saraph, Seaton, and Shemming 1969) are questionable. These were calculated without including excitation resonances which can markedly increase the collision strengths. An example of this is the recent calculation of collision strengths for the noninverted ^3P multiplet in Ne V (Aggarwal 1983). These indicate that the previous values for Ne V given by Saraph, Seaton, and Shemming (1969) were underestimates by an order of magnitude due to the exclusion of resonances. Such an enhancement by resonances would increase the infrared line emission per ion and so decrease the derived Ne III abundance. An increase by a factor of 2.9 in the $\Omega(^3P_2\text{–}^3P_0)$ collision strength would bring the infrared abundance into agreement with the optical result.

A further check on the value of $\Omega(^3P_2-^3P_0)$ can be made by deriving an electron temperature through comparison of the 36 μm and 3868 Å fluxes integrated over the nebula. The integrated 3868 Å to Hβ flux ratio has been measured photometrically by Tamura (1970). The integrated Hβ flux has been measured by Capriotti and Daub (1960). Using an Hβ extinction constant of $c(\text{H}\beta) = 0.18 \pm 0.11$ (Cahn 1976) and the Whitford reddening curve as tabulated by Kaler (1976) to deredden the 3868 Å flux, the [Ne III] 3868 Å flux is $(1.85 \pm 0.63) \times 10^{-17}$ W cm^{-2}.

From the integrated 36.02 μm/3868 Å flux ratio, the atomic parameters mentioned above, and an assumed density of 4000 cm^{-3}, the derived electron temperature is T_e(Ne III) = 6900(+700, −400) K, considerably lower than the O III temperatures given by Reay and Worswick (1982). Increasing $\Omega(^3P_2-^3P_0)$ by a factor of 2.9, the result is 8400(+1200, −600) K, bringing the two determinations into better agreement. This supports our claim that $\Omega(^3P_2-^3P_0)$ is underestimated. A recalculation of the ^3P collision strengths which includes resonance effects would clarify the situation.

Depending on the detailed results of more accurate calculations, the 36.02 μm to 15.56 μm line ratio might be an accurate, temperature-insensitive measure of electron density. Such density measurements will be a useful supplement to optical results. The density range over which any infrared line ratio is sensitive is dependent on the collision strengths. With the Saraph, Seaton, and Shemming (1969) values, the 36 μm to 15 μm line ratio is sensitive over the range of approximately $1.3 \times 10^{+4}$ to $1.3 \times 10^{+5}$ cm^{-3}. This is rather high for planetary nebulae, but the sensitivity range would shift to lower densities with increased collision strengths. An order of magnitude increase in all of the ^3P collision strengths would shift the sensitivity range to approximately 10^3–10^4 cm^{-3}.

IV. CONCLUSIONS

We have presented the first detection of the [Ne III] 36.02 μm line in a planetary nebula—NGC 6543. In principle, this line is a useful probe of the abundance of Ne III, the dominant form of neon in objects of medium to high excitation. The derived abundances are quite insensitive to temperature uncertainties or spatial variation in the nebula.

Unfortunately, these and possible future measurements of this line cannot be used until the associated atomic parameters are known accurately. The discrepancy between the infrared and optical line abundances may be due to inaccuracies in the $\Omega(^3P_2-^3P_0)$ collision strength for Ne III. These may be the result of neglected resonance effects in past atomic calculations. We therefore urge the recalculation of these numbers. Once accurate parameters are available, the 36.02 μm line can be used with existing 3868 Å or future 15.56 μm fluxes as a temperature or density probe, respectively, in objects of medium to high excitation such as planetary nebulae and Seyfert galaxies.

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G. E. Gull, J. R. Houck, and M. A. Shure: Astronomy Department, Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853-0352

T. Herter: Grumman Aerospace Corporation, Mail Stop A01-26, Bethpage, NY, 11714