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# SEARCH FOR $HeH^+$ IN NGC 7027

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## ABSTRACT

We have searched the 3.3 $\mu$m spectrum of the planetary nebula NGC 7027 for the $R(0)$ line of the fundamental vibration-rotation band of the molecular ion $HeH^+$ without detecting it. The upper limit for detection is $3.7 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, an improvement in excess of 100 over previous published attempts. This limit is low when compared to expectations based on analysis of molecular processes in gaseous nebulae. Likely causes are incorrect radiative association rates or inadequate representation of the nebular size or of the density distribution in the outer boundary of the nebular model used for the flux prediction.

*Subject headings:* molecular processes — nebulae: abundances — nebulae: individual (NGC 7027) — nebulae: planetary

### I. INTRODUCTION

Although helium and hydrogen are the two most abundant nuclear constituents in the universe, the helium hydride ion ($HeH^+$) has not been detected in nature, despite its potential for long life under certain low-density astrophysical conditions. This apparent absence has not prevented theoretical study since the ion is isoelectronic with the $H_2$ molecule. In addition, $HeH^+$ can be studied experimentally in the laboratory where it can be manufactured in small quantities (Bernath and Amano 1982).

The possible association of $HeH^+$ with the bright planetary nebula NGC 7027 began with Dabrowski and Herzberg (1978) who suggested the ion might be responsible for the strong 3.3 $\mu$m emission feature found by Merrill, Soifer, and Russell (1975) in this and in various other sources including H II regions and extragalactic objects. This suggestion has proved untenable (Scrimger *et al.* 1978). Suggested explanations for the 3.3 $\mu$m emission, together with a family of infrared features, now include emission by dust particles, as first suggested by Russell, Soifer, and Merrill (1977), or by polycyclic aromatic hydrocarbons (PAH) as suggested by Duley and Williams (1981) and by Leger and Puget (1984). However, the discovery of $H_2$ in NGC 7027 by Treffers *et al.* (1976) has maintained interest in the molecular chemistry inside ionized plasmas. A detailed study by Black (1978) concluded that both $H_2$ and $HeH^+$ could exist inside the ionized region of a nebula near the edge of the ionization front. Roberge and Dalgarno (1982, hereafter RD) further studied the production and destruction mechanisms. They predicted the emission strength for transitions in the vibration-rotation bands of $HeH^+$ for NGC 7027.

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Several observations of the 3.3 $\mu$m region in NGC 7027 have been reported (Merrill, Soifer, and Russell 1975; Russell, Soifer, and Merrill 1977; Tokunaga and Young 1980; Geballe *et al.* 1985). All were made at low ($\sim 50$) to medium ($\sim 750$) resolving power which did not permit a sensitive search for this ion. Here we report observations made for the first time at high resolving power (6000) specifically in order to detect the predicted emission of $HeH^+$. These observations fail to detect any $HeH^+$ with an upper limit which is incompatible with the predictions of RD. First we describe the observations and the derived upper limits, and then we discuss some of the consequences of this nondetection.

### II. OBSERVATIONS

The telluric transmission spectrum in the 3.3 $\mu$m region contains many absorption features, mostly due to water and $\nu_3$ band of methane, many of which totally absorb in one air mass and can effectively block the detection of emission lines. In addition, the nebula itself contributes a continuum and recombination lines of H and He. The detection prospects for each $HeH^+$ transition have to be investigated individually. For $HeH^+$ we used the measured laboratory wavenumbers of Bernath and Amano (1982), who give values for the transitions $R(0)$ through $R(4)$ and for $P(1)$ through $P(4)$ with a precision of 0.001 cm$^{-1}$. For the telluric transmission spectrum, initially we used the solar spectrum as observed at Kitt Peak by Delbouille *et al.* (1981). The conclusion for each line is summarized in Table 1.

In Table 1 the first two columns give the line designation in the fundamental band of $HeH^+$ and the wavenumber measured by Bernath and Amano (1982). An estimate of the average telluric transmission over the bandwidth corresponding to the sum of the expected line width and Doppler shift is given in column (3); lowered transmission is due to overlapping wings of distant strong water absorptions. Telluric

TABLE 1

TELLURIC INTERFERENCE WITH $HeH^+$ LINES

| $HeH^+$ Line (1) | $\tilde{\nu}$ ($cm^{-1}$) (2) | Average Transmission (3) | Line Absorption (4) | Comments (5) |
|---|---|---|---|---|
| $R(4)$.............. | 3157.297 | 70% | $CH_4$ | Wings of strong water absorption |
| $R(3)$.............. | 3121.077 | 30 | ... | Very strong water absorption |
| $R(2)$.............. | 3077.992 | 0 | ... | Total water absorption |
| $R(1)$.............. | 3028.375 | 60 | $H_2O$, $CH_4$ | Strong line absorption |
| $R(0)$.............. | 2972.573 | 70 | ... | On wing of $H_2O$ |
| $P(1)$.............. | 2843.904 | 80 | $H_2O$ | Moderate line absorption |
| $P(2)$.............. | 2771.806 | 90 | $CH_4$ | Strong line absorption |
| $P(3)$.............. | 2695.050 | 90 | $H_2O$ | Moderate line absorption |
| $P(4)$.............. | 2614.030 | 90 | $H_2O$ | Weak line absorption |

absorption lines that occur within this bandpass are identified in column (4) with comments on the individual region appearing in column (5). All of the $HeH^+$ transitions are potentially affected by telluric absorptions. By observing from Mauna Kea we could expect better transmission. From a spectrum of IRC +10216 taken there by Maillard *et al.* (1987), the transmissions at the positions of $R(1)$, $R(0)$, and $P(1)$ are 90%, 97%, and 100%, respectively.

RD predict that the excitation of $HeH^+$ will not be in thermal equilibrium and will favor the upper level ($v = 1$, $J = 1$) of the transitions $R(0)$ and $P(2)$ for which they give flux predictions. Of these, $P(2)$ is likely unobservable because the feature falls 0.6 $cm^{-1}$ from the expected hydrogen recombination line H20-6. The other predicted line, $R(0)$, is one of the more favorable, but since it is on the wing of a strong telluric absorption line, favorable conditions for detection require that the air path be as dry as possible. For $P(4)$ the interference from telluric absorption is less than for $R(0)$, but the effect of foreground telluric thermal emission is more severe at the wavenumber of $P(4)$ so the detection limit cannot be as good. There is no flux prediction, but the theoretical expectation is for a far weaker line than either $R(0)$ or $P(2)$. The other candidates with any potential for ground-based observation are $R(1)$, $P(1)$, and $P(3)$.

To minimize the noise introduced by the foreground thermal emission, the bandpass was restricted by a liquid nitrogen–cooled, narrow-band filter to 200 $cm^{-1}$, roughly centered on $R(0)$, but including $P(1)$ and $R(1)$ at half-maximum transmission. An additional set of filters for $P(4)$ were installed in the dewars, but circumstances and available telescope time did not allow us to make any observations of the $P(4)$ region.

The observations were made with the Fourier Transform Spectrometer of the 3.6 m Canada-France-Hawaii Telescope (CFHT) on Mauna Kea. The design of this instrument is described by Maillard and Michel (1982). The recorded interferogram is the difference in signals through two entrance apertures, one receiving the source and the second monitoring an identical area of the sky 53″ away. This arrangement approximately removes the foreground thermal emission. To cancel it more completely, a second interferogram is measured immediately afterward with the source and sky switched between the entrance apertures. These sequential pairs are subsequently subtracted, and one such pair forms the minimum data sample.

The entrance aperture was chosen to be 8″. A larger aperture would have included more of the nebula as it is about 11″ by 18″ angular size in the visual (Perek and Kohoutek 1967), but the spatial distribution of the ionized gas measured at radio wavelengths of 6 cm (Scott 1973) and 2 cm (Harris and Scott 1974) shows a more compact source with a full width at half-maximum of the order of 7″.5, which is confirmed from a mapping through the Br$\gamma$ line (Beckwith *et al.* 1980). The $HeH^+$ is supposed to be concentrated in a shell at the limit of the ionized region (Black 1978) and would be within the aperture. A larger aperture would have considerably increased the noise from the thermal foreground without a comparable gain in signal. The nebula was positioned on the entrance aperture by maximizing the nebular signal reaching the detectors, and this position was held by offset guiding on a convenient star. This centering was checked after every two scan pairs. The centering process indicates that most of the available nebular radiation in the bandpass reached the detectors.

To determine the optimum resolution we have made use of a spectrum in the Br$\gamma$ region from Thronson (1983) which shows that the half-power widths of the H and He recombination lines are 50 km $s^{-1}$. The $H_2$ emission lines are not substantially wider than this value (Smith, Larson, and Fink 1981). We can expect any $HeH^+$ emission to have a similar value. We therefore set the unapodized resolution to correspond to 50 km $s^{-1}$ or 0.5 $cm^{-1}$ to maximize the detection chance against the nebular continuum. The telluric features, however, are not fully resolved. The spectra have been reduced with weak apodization.

The observations were made on three consecutive nights starting 1986 September 18/19. The number of interferogram pairs obtained is listed in Table 2. Each pair represents 30 minutes of observing time, and each was individually trans-

TABLE 2

OBSERVATIONS OF NGC 7027

| Date (1986 Sep) (1) | sec $z$ (2) | Scan Pairs (3) | Relative Humidity (4) | Temperature (°C) (5) |
|---|---|---|---|---|
| 18/19A......... | <1.20 | 6 | 30% | 2 |
| 18/19B......... | >1.20 | 5 | 40 | 1 |
| 19/20A......... | <1.20 | 3 | 70 | 4 |
| 19/20B......... | >1.20 | 5 | 70 | 3 |
| 20/21A......... | <1.20 | 7 | 50–80 | 3 |
| 20/21B......... | >1.20 | 2 | 80 | 2 |

formed and inspected for quality. Individually none of these yields much useful information on $HeH^+$, except to show that its emission is not present in considerable strength. To improve the signal to noise ratio, the spectra were subsequently summed in two sets for each night depending on the zenith distance: (*A*) sec $z < 1.20$ and (*B*) sec $z > 1.20$. Observations of NGC 7027 were halted when the value of sec $z$ exceeded approximately 2.2. These summed sets were investigated individually, in several combinations, and finally summed to give a single spectrum.

The nights were not of high quality for the CFHT site. During the second and third nights the relative humidity was high, and observations were halted at times. Spectra from the third night have a significantly higher noise level than the others. The best quality spectra come from the first night when the column water content was smaller than on the other two nights.

Several stars were observed on the second night with a similar set-up but with an entrance aperture of 5″.

None of the various sums of spectra show any evidence of a $HeH^+$ emission feature, although other emission features do show clearly. Various algorithms have been applied to combine the NGC 7027 spectra with combinations of standard stars to (1) remove the filter transmission to produce a flat continuum and (2) remove the telluric absorption as well as possible. Additional emission lines are found with these procedures, but no features show up near the $HeH^+$ positions. The other spectroscopic features unrelated to the $HeH^+$ will be discussed in another paper.

The region near *R*(0) is shown in Figure 1 with a representative stellar spectrum shown as a comparison for the telluric components. Note that the telluric spectrum is not completely resolved so that the stellar spectrum cannot be considered to be the telluric transmission spectrum. The result of one of the more successful line detection algorithms is also shown.

Although no line is detected at *R*(0), the noise level in the summed spectrum indicates a realistic detection upper limit is about 7% of the continuum flux. For $HeH^+$ a reasonable expectation for the line width would be 0.7 $cm^{-1}$ from a combination of 0.5 $cm^{-1}$ Doppler width convolved with an equal instrumental width. This produces an emission equivalent width of 0.05 $cm^{-1}$ as an upper limit, which must be increased by a factor of 1.2 to allow for the absorption by the wing of the water band nearby. For a flux calibration we measure on a calibrated spectrum of Geballe *et al.* (1985) that the continuum at *R*(0) is 0.6 Jy or $1.8 \times 10^{-13}$ ergs $cm^{-1}$ $s^{-1}$. This flux is measured through a 4″ aperture and must be increased by a factor of 3.4 to correspond to our 8″ aperture as described below. The resulting limit on the *R*(0) flux is then $3.7 \times 10^{-14}$ ergs $cm^{-2}$ $s^{-1}$. Table 3 gives results for a comparable estimate for each $HeH^+$ line in the bandpass. For *R*(1) the continuum is affected by the 3.3 $\mu$m dust feature, so the ratio relative to the continuum is not given in Table 3.

TABLE 3

UPPER LIMITS TO $HeH^+$ EMISSION

| Line (1) | $F_{\tilde{\nu}}/F_{\tilde{\nu}c}$ (2) | $W_{\tilde{\nu}}$ ($cm^{-1}$) (3) | Flux (ergs $cm^{-2}$ $s^{-1}$) (4) |
|---|---|---|---|
| *R*(0)......... | <0.07 | <0.05 | $<3.7 \times 10^{-14}$ |
| *P*(1)......... | <0.25 | <0.18 | $<10^{-13}$ |
| *R*(1)......... | ... | <0.13 | $<7 \times 10^{-14}$ |

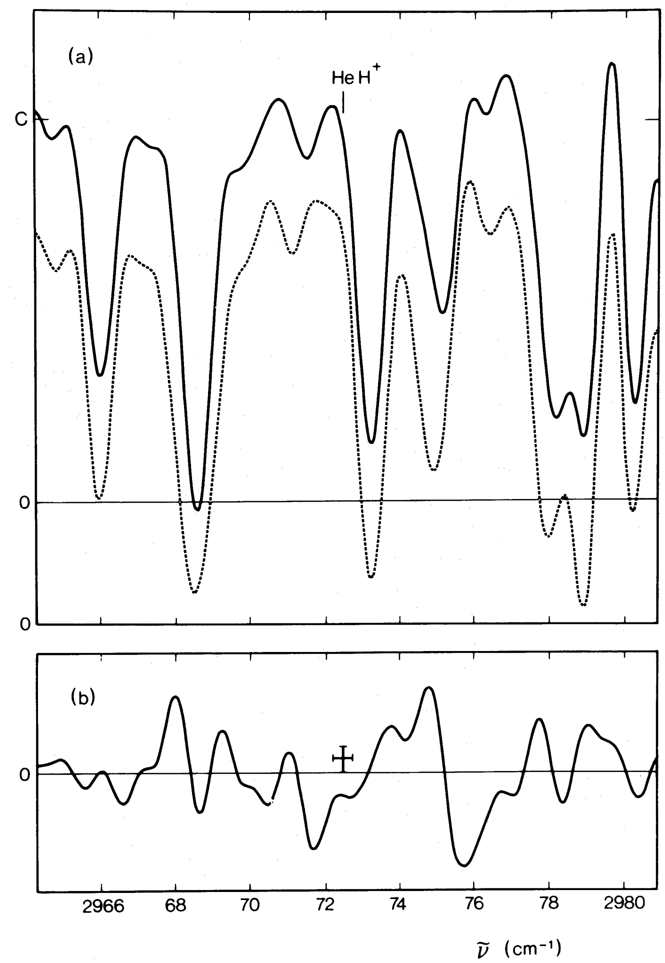


FIG. 1.—(*a*) The bold line is the spectrum of NGC 7027 from the sum of all the scans with air mass less than 1.20. The continuum corresponding to the adopted calibration is marked. The expected location of the *R*(0) $HeH^+$ line is marked at the same Doppler displacement as the nebular H and He recombination lines, which are outside the wavenumber range depicted. The dashed line is a spectrum from a single scan pair of a standard star, $\alpha$ Per, to show the nature of the telluric absorption. This spectrum has been scaled to the same continuum level and then displaced downward to avoid considerable overlap. (*b*) The output of one line detection algorithm with the same vertical scale as part (*a*). The cross marks the expected location of the $HeH^+$ *R*(0) line with the expected half-width and the upper limit given in the text. This upper limit is based on the complete sample of data and not just this displayed portion.

Our upper limit for *R*(0) represents an improvement in excess of 100 over previous published attempts to detect this feature (Tokunaga and Young 1980). An upper limit given by Smith *et al.* (quoted in Russell, Soifer, and Merrill 1977) is $5 \times 10^{-12}$ ergs $cm^{-2}$ $s^{-1}$, but the region searched was from 3028 to 3051 $cm^{-1}$. Subsequent precise line position measurements (Bernath and Amano 1982) show that this region is between *R*(1) and *R*(2), and therefore the Smith limit does not apply to $HeH^+$. As will be discussed below, our upper limit is also low when compared to the range of flux predictions by RD.

The detection limits in columns (2) and (3) of Table 3 depend mostly on our estimate of the noise level and the instrumental sensitivity at the expected wavenumber. We regard these numbers to be realistic assessments. The conversion to flux in column (4) depends, in addition, on the calibration from Geballe *et al.* (1985) and upon our conversion for the difference in apertures. For the latter effect we assumed the distribution of ionized gas was represented by the 5 GHz map of Scott (1973) at 2″ spatial resolution. We further assumed that each aperture was centered on the maximum signal. If we use instead the distribution of ionized gas and dust as represented by the map of the 11.4 $\mu$m emission by Bentley (1982) at 3″.5 spatial resolution, we get a value only 7% larger. The aperture correction is sensitive to the degree of source concentration, and the maps include some instrumental broadening. The adopted factor of 3.4 may, therefore, be somewhat too large, so the flux limits in Table 3 might be reduced slightly. The only other calibration in this spectral range is given by Merrill, Soifer, and Russell (1975). With aperture corrections applied in the manner just described, the two calibrations are inconsistent by a factor of two in the sense that the Merrill, Soifer, and Russell calibration gives larger fluxes at several wavelengths compared to the Geballe *et al.* calibration. We tend to prefer the Geballe *et al.* calibration because the resolving power is higher; however, even their spectrum does not resolve the hydrogen recombination lines. The amount of uncertainty due to these causes does not significantly affect the comparison with the predictions which follows.

## III. DISCUSSION

### *a) The Flux Prediction*

RD predict fluxes of 2.0 for $R(0)$ and 5.5 for $P(2)$ (note: a minor misprint in RD reverses these numbers; Dalgarno 1987), both in units of $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, for the model used by Black (1978) located at a distance of 1.8 kpc. Black's model was in turn derived from one developed by Flower (1969*a*). Although the model was not specifically developed for NGC 7027, RD state that it matches the observed characteristics of the nebula in several respects. They further note that the nebula has regions of higher density by an order of magnitude, which results in the predicted fluxes being enhanced by a factor of up to 100. On this basis, the flux prediction for $R(0)$ may be as high as $2 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$. Comparison with the observations in Table 3 indicate that the $R(0)$ transition would have been readily detected if it had been present at this level of flux. Indeed, the limit observed effectively rules out any enhancement due to higher densities in the actual nebula as suggested by RD.

Unfortunately the stronger expected line at $P(2)$ is probably unobservable due to telluric absorption and nebular hydrogen emission (see Table 1) at flux levels consistent with the upper limit at $R(0)$.

Clearly there is a discrepancy between the prediction and the observed upper limit for the $R(0)$ flux. The resolution of the difficulties appears to encompass the following possibilities:

1. The rate of a major reaction that produces $HeH^+$ is too large so that the abundance of $HeH^+$ is overestimated.
2. The rate of a major reaction that destroys $HeH^+$ is too small, or some such reaction has not been included.
3. The excitation rate to ($v = 1, J = 1$) is overestimated.
4. The nebular model is not an adequate representation of NGC 7027.

These possibilities are explored in the sections below.

### *b)* $HeH^+$ *Abundance*

The most direct explanation would be that the column density of the $HeH^+$ is not as great as expected. In the RD prediction the $HeH^+$ abundance is in steady state reached by production by radiative association of $He^+$:

$$He^+ + H \rightarrow HeH^+ + h\nu\ , \tag{1}$$

and by associative ionization of He excited to the metastable $2\,^3S$ level:

$$He(2\,^3S) + H \rightarrow HeH^+ + e\ . \tag{2}$$

More exotic reactions do contribute; for example,

$$H_2{}^+ + He \rightarrow HeH^+ + H\ , \tag{3}$$

as discussed by Black (1978). RD claim that the contribution of reactions (1) and (2) to the column density is much more important than that of reaction (3) and that this situation prevails over a wide range of conditions. As a result, RD predict a column density of $1.5 \times 10^{12}$ cm$^{-2}$, which is larger than Black's prediction from the same model by 300 times.

The rate coefficients for reaction (2) have been studied, both theoretically and experimentally, by several investigators; see RD for references. In view of the variety of studies, these rate coefficients do not seem a likely cause of concern. In contrast, the rate coefficient for reaction (1) is more uncertain. There is no experimental work on it; the rate is based on the calculations of Sando, Cohen, and Dalgarno (1971) over a temperature range of 50 to 1000 K. The rate used by RD to support the importance of reaction (1) had to be extrapolated over an order of magnitude in temperature to $10^4$ K.

In addition to the rate coefficients, the contribution of particular reactions to the $HeH^+$ column density depends on the local concentration of the individual reactants. For reaction (3) the relative contribution is obviously highly model-dependent since one reactant is $H_2{}^+$, whose chemistry in turn must be treated as completely as $HeH^+$. In the context of this study this uncertainty is unimportant since reaction (3) contributes only 0.3% to the $HeH^+$ concentration. In the case of reactions (1) and (2) the reactants are major components of the ionization structure of the model. To question their concentrations is to question the essentials of the model itself. This issue is considered below in the section dealing with the model.

A related possibility is reduction of the $HeH^+$ abundance by increasing the rate of destruction. In the situation appropriate for NGC 7027 the main destruction mechanism is photodissociation:

$$HeH^+ + h\nu \rightarrow He^+ + H\ . \tag{4}$$

The cross sections have been computed by Saha, Datta, and Barua (1978) and by RD. One model-dependent uncertainty occurs because $HeH^+$ is shielded from the destructive photons by neutral He. An additional effect, noted by RD, is that dust absorption may remove photons as well. In the flux predictions no allowance seems to have been made for this latter effect, but the immediate consequence of its inclusion would be to increase the steady state abundance of $HeH^+$, contrary to the observational problem.

An additional possibility remains that an important destruction mechanism has gone unidentified. In this event its destructive effectiveness for $HeH^+$ must be several times greater than equation (4). Equivalently, the rate of a known destructive process may be much larger than currently believed; in this event the actual destructive effectiveness must be several times that of equation (4).

### c) $HeH^+$ *Excitation*

It may be that the analysis of $HeH^+$ excitation has been incomplete, so that we have not looked for the strongest transitions. The excitation of $HeH^+$ has been discussed by RD who also calculate the radiative lifetimes of the excited states. The principal excitation process is electron impact for which the cross section has been estimated by Boikova and Ob'edkov (1968). At the conditions appropriate for NGC 7027 the vibrational populations fall far below thermal equilibrium values and the rotational populations are not thermal until the electron density, $N_e$, exceeds $10^5$. The original model used $N_{tot} = 7000\ cm^{-3}$. Although parts of NGC 7027 have $N_e \approx 10^5$, these are the central regions which do not contain the $HeH^+$. The outer regions have $N_e \approx 10^4$, so thermal redistribution of the rotational levels is still not a problem. Neither electron impact nor ultraviolet pumping, which is also considered by RD, are adequate to provide enough rotational redistribution to resolve the discrepancy.

### d) *Basic Model*

The comments in the above sections assume that the model developed by Flower and used by RD provides accurate number densities of hydrogen, helium, their ions, and free electrons for the nebula. NGC 7027 is a reasonable choice of object to observe since it has an extreme surface brightness, but it may be difficult to model since its structure is by no means obvious from its visible appearance (see the photograph in Minkowski 1968). On the other hand, radio observations (Balick, Bignell, and Terzian 1973) indicate that the ionized gas has a distribution consistent with that of other planetary nebulae. Either absorption by the interstellar medium or interaction between it and the nebular ionization front or both alter the visible nebula considerably. On this basis, a model derived from a traditional picture of a planetary nebula seems reasonable.

The $HeH^+$ flux predictions start with a self-consistent model of the ionization structure computed by Flower (1969*a*). He seems to have chosen the parameters with a different planetary nebula in mind, namely NGC 7662 (Flower 1969*b*). Black (1978) used this model to compute the distributions of various molecules including $HeH^+$, for which he obtained a column density of $4.7 \times 10^9\ cm^{-2}$. RD considered $HeH^+$ in more detail and included the effects of reactions (1) and (2) with the same model, obtaining a column density of $1.5 \times 10^{12}\ cm^{-2}$, a factor of 300 larger. For their flux prediction and its association with NGC 7027, RD adopted a distance of 1.8 kpc in place of the original 1.61 kpc, presumably to correspond to the distance determined by O'Dell (1962). If we convert back to the original distance, the predicted $R(0)$ flux becomes 25% larger, thereby increasing the discrepancy with observation. More recent discussions of the distance in the literature make the matter worse with generally smaller distances: 1.48 kpc (Cahn and Kaler 1971), 1.3 kpc (Jura 1984), and between 1 and 1.5 kpc (Pottasch *et al.* 1982).

If we now compare the model with the observed properties of NGC 7027, an important difference occurs in the density, as noted by RD. In the regions sampled by the forbidden lines usually used to establish nebular densities, the model has an electron density of $8 \times 10^3\ cm^{-3}$. Observationally the measurements of electron density in the nebula run higher: $6 \times 10^4\ cm^{-3}$ (Perinotto, Panagia, and Benvenuti 1980), $5.7 \times 10^4\ cm^{-3}$ (Atherton *et al.* 1979), and $3 \times 10^4\ cm^{-3}$ (Kaler *et al.* 1976). The latter authors get higher electron densities of $10^5\ cm^{-3}$ from high excitation forbidden lines and $10^6$ to $10^7\ cm^{-3}$ for H and He II lines, but these values pertain to the inner regions of the nebula where there is no $HeH^+$ expected. These densities are somewhat short of the factor of 10 in density used by RD to extrapolate their flux prediction. Additionally, in the model computed by Black (1978) the $HeH^+$ is confined to a thin shell of thickness $0.02R_{neb}$. The midpoint of this shell has an electron density of $10^3\ cm^{-3}$, and this density is decreasing rapidly outwards throughout the shell. It is not clear that the $HeH^+$ density in this shell will scale directly as the density of the more fully ionized portion of the nebula. The possibility exists that the extrapolation of the flux for higher densities has been excessive.

Furthermore, the model fails to match the size of the nebula. For example, Kaler *et al.* (1978) give the nebular radius as 0.051 pc (at a distance of 1.48 kpc, or an apparent angular diameter of 14″) compared to the model's 0.091 pc. If we assume the thickness and density of the $HeH^+$ shell are unchanged, scaling the model down to a radius of 0.051 pc would change the predicted flux by a factor of 0.3. As an alternate comparison, at the distance of 1.8 kpc assumed by RD, Flower's model has an apparent angular diameter of 21″. The nebular diameter derived by Scott (1973) from his map at 5 GHz is 6″.5. Scaling the model to this size in the same manner as before would change the predicted flux by a factor of 0.1. An improved choice of nebular size should make the flux predictions more consistent with the observed upper limits.

It is well established that the apparent volume represented by the angular diameter when combined with the electron density does not yield the correct flux at H$\beta$ (Kaler *et al.* 1976; Aller 1954). Correcting this deficiency introduces a parameter, $\epsilon$, the volume filling factor, which introduces large unfilled holes in the volume. The values of $\epsilon$ are so small, however, that these authors have concluded that, in addition, the material must be in clumps or filaments. If a filamentary structure with the same volume filling factor applies to the $HeH^+$ shell, the column density could be reduced by a factor of 10. This problem introduces an additional uncertainty in the nebular geometry.

No single factor considered above will resolve the observational discrepancy by itself, but the combined effects may. Newer ionization models exist specifically for NGC 7027. Scott (1973) has a cylindrical model to represent the radio emission maps. A spherical model of the ionization structure has been computed by Shields (1978) for the purpose of abundance determinations. Atherton *et al.* (1979) have used a variety of mapping data to derive a prolate spheroid model. It seems appropriate to suggest the need of a model of the $HeH^+$ distribution, starting with a reconsideration of the appropriate choice of nebular parameters for NGC 7027.

## IV. CONCLUSIONS

We have searched for the $R(0)$ line of the fundamental band of the molecular ion $HeH^+$ in the planetary nebula NGC 7027. The line is undetected down to a flux limit of $3.7 \times 10^{-14}$ ergs $cm^{-2}\ s^{-1}$. This limit is an improvement of a factor of 100 over previous published attempts to detect this ionic molecule in this nebula.

Our limit is low compared to expectations based on studies of the gas phase molecular processes in the nebula. This result suggests that the $HeH^+$ density is much lower than expected.

We have suggested the following areas where the $HeH^+$ modeling needs reexamination:

1. The rate of radiative associative formation of $HeH^+$ from $He^+$ and H may be overestimated.
2. The density distribution in the nebula has not been treated in the correct detail.
3. When applying a nebular model to NGC 7027 the choice of parameters, particularly the size of the nebula, needs to be reconsidered.

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