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NEAR-INFRARED SPECTROSCOPY OF POSSIBLE PRECURSORS TO PLANETARY NEBULAE: AFGL 618

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ABSTRACT

A spectrum in the range 1.9–2.5 μm of the suspected protoplanetary nebula AFGL 618 is presented. It shows at least 11 members of the H_2, $v=1\rightarrow0$ and $v=2\rightarrow1$ rotation-vibration branches. These lines appear to arise in a dusty region of shocked gas, and the line intensities are used to estimate shock velocity, preshock density, H_2 excitation temperature, and extinction to the emitting region. The observations are consistent with the suggested geometry of a double-lobed reflection nebula, banded about the center with a ring of dusty material from which the H_2 lines are emitted.

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

I. INTRODUCTION

The class of object suspected to be protoplanetary nebulae has recently been the center of significant attention at radio and infrared wavelengths. This is due in large part to the important role played by planetary nebulae—and consequently their progenitors—in the advanced stages of stellar evolution. In addition, there are significant source characteristics that can be uniquely determined from infrared and radio observations: mass-loss rates and velocities, total luminosities, source dynamics and excitation. Finally, there is a particular attraction to protoplanetaries for the radio or infrared astronomer: unlike other stages of stellar evolution (e.g., the extremely young), the class of object that precedes the protoplanetary (i.e., the red giant) and the subsequent state (i.e., young planetary nebula) are well known and reasonably well studied. This puts desirable constraints on theoretical models and observational conjectures.

AFGL 618 is one of the best-known of protoplanetary nebulae. It was the subject of extensive infrared and visual study by Westbrook *et al.* (1975), who first suggested the evolutionary stage of the object on the basis of its emission spectrum and geometry. Further infrared observations were reported by Russell, Soifer, and Willner (1978) who presented 2–8 μm spectrophotometry that showed a smooth continuum with no positively detected features. With the far-infrared observations of Kleinmann *et al.* (1978), the infrared spectrum appears clearly dominated by continuum dust emission. The broad-band flux densities from 2 μm out to 50 μm suggest a range of characteristic dust temperatures of $\sim$400 to $\sim$100 K to be found in the source. Without significant 10 μm "silicate" absorption or emission, the dust in AFGL 618 is likely to be graphite or related composition. Calvet and Cohen (1978) produced an extensive study of bipolar nebulae, including visual spectroscopy of AFGL 618. More recent visual observations—spectroscopy, spectropolarimetry, and a detailed model—have been presented by Schmidt and Cohen (1981).

At radio wavelengths Lo and Bechis (1976) reported weak CO emission, apparently from an expanding neutral cloud surrounding the central obscured star. Zuckerman, Terzian, and Silverglate (1980) searched for 21 cm H I emission, but due to confusion from strong, unassociated galactic contamination could not make a definite detection. AFGL 618 is a radio-continuum source (Wynn-Williams 1977; Kwok 1980, private communication) that is optically thick at least to 2 cm and may be becoming brighter with time.

Despite the rich and interesting visual spectrum of AFGL 618, no moderate or high-resolution spectra have been obtained beyond about 1 μm. Beckwith, Persson, and Gatley (1978) detected the $v=1\rightarrow0$ $S(1)$ line of H_2 at 2.12 μm. This is indicative of expanding, shocked material and, along with the visual emission lines, suggests an energetic, active source. A number of the other $v=1\rightarrow0$, H_2 lines that are expected to be strong lie in the 1.9–2.5 μm region. It will be necessary to measure these to determine the characteristics of the H_2 excitation. The useful Brackett γ (Bγ) line of atomic hydrogen also falls in this wavelength range. This line has been important in estimating source extinction and excitation parameters of other dust-embedded stars. For these reasons, near-infrared spectra have been obtained of the protoplanetary nebula AFGL 618.

The following section describes the observations and data reduction. Section III includes analysis and discussion.

II. OBSERVATIONS

a) *Technique*

AFGL 618 was observed on several occasions during the latter part of 1980 with the Steward Observatory Fourier Transform Spectrometer (SOFTS): October 27 and December 25, 26. The SOFTS was mounted at the Cassegrain focus of the Steward Observatory 2.3 m telescope. A pair of liquid-He–cooled InSb photoconductors were used as detectors. A spectral resolution of 2 cm^{-1} ($\Delta\lambda/\lambda=4\times10^{-4}$ at 2 μm) was used. The instrument was operated in a dual-beam mode with sky subtraction referenced to points 30″ east and west of the source. The data were obtained by maximizing the near-infrared signal through the 8″ aperture and broad-band filters and integrating on that position. The total integration time was about $5^h\ 20^m$.

Telluric absorption was corrected by observing G stars at air masses close to that of AFGL 618. The relative intensities in the spectrum were determined by observing an A star and assuming that its near-infrared color temperature was 10^4 K. The resultant spectrum is shown in Figure 1, with normalized flux density plotted against wavenumber. The legend for the figure (described in the caption) identifies the positions of atomic and molecular hydrogen. The relative intensities are presented in Table 1. Their statistical uncertainties were estimated from the continuum noise on either side of a line.

b) *Line Strengths*

i) *Relative Values*

The outstanding feature of Figure 1 is the numerous strong members of the H_2, $v=1\rightarrow0$ rotation-vibration

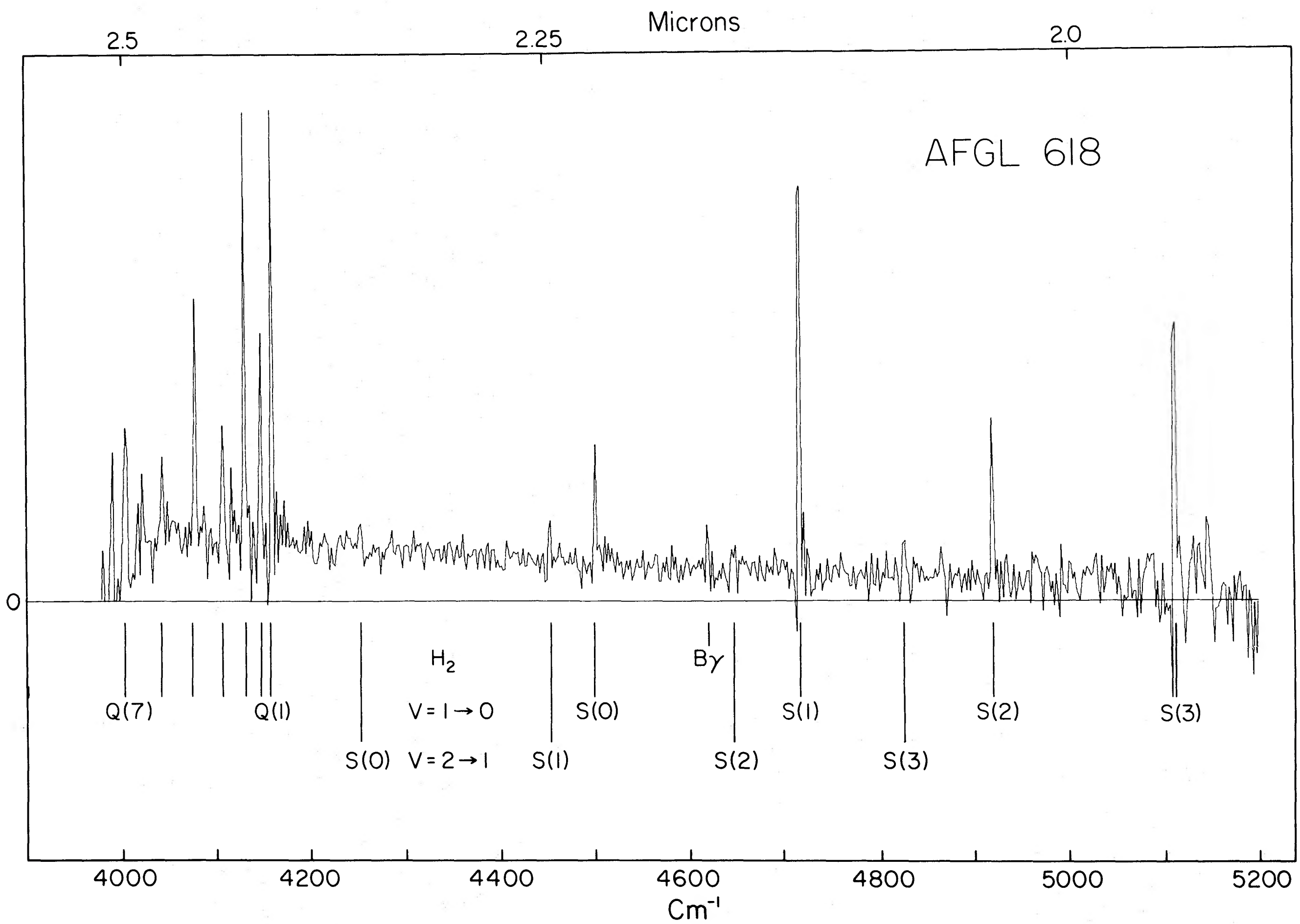

FIG. 1.—The near-infrared spectrum of AFGL 618. The verticle scale is linear in flux density. The identified lines are indexed in the lower portion of the figure. The upper row shows the positions of the H_2, $v=1\rightarrow0$ rotation-vibration series. Beneath it are the positions of the $v=2\rightarrow1$ lines. Also indicated is the position of the Brackett γ line.

TABLE 1
LINE FLUXES[a]

Line Value			
$H_2, v=1\rightarrow 0$		$H_2, v=2\rightarrow 1$	
$S(0)$ ...	0.20 ± 0.02	$S(0)$ ...	0.07 ± 0.02
$S(1)$ ...	1.00 ± 0.03	$S(1)$ ...	0.09 ± 0.02
$S(2)$ ...	0.33 ± 0.02	$S(2)$ ...	0.03 ± 0.015
$S(3)$ ...	0.67 ± 0.06	$S(3)$ ...	0.10 ± 0.02
$Q(1)$ ...	0.83 ± 0.04		
$Q(2)$ ...	0.27 ± 0.04	Hydrogen	
$Q(3)$ ...	0.68 ± 0.04		
$Q(4)$ ...	0.21 ± 0.03	Bγ......	0.08 ± 0.02
$Q(5)$ ...	0.36 ± 0.03		
$Q(6)$ ...	0.13 ± 0.05		
$Q(7)$ ...	0.25 ± 0.05		

[a]Fluxes normalized to 1.00 for the $v=1\rightarrow 0$ $S(1)$ line. As described in the text $1.00\equiv 1.4\times10^{-12}$ ergs cm^{-2} s^{-1}. Quoted uncertainties are 1 σ and statistical only. Systematic uncertainties are estimated to be $\pm$10–20%.

series: Table 1 lists 15 lines at least as strong as 2 σ. In no case was a line seen to be shifted or broadened to a degree greater than the 2 cm^{-1} resolution of these observations. The uncertainties quoted in the table are statistical only, and the data are subject to some systematic uncertainties which should be noted.

Imperfect correction for telluric absorption can affect line strengths and widths, or increase noise. The greatest effect is at the atmospheric H_2O edges beginning near 5200 cm^{-1} [very close to the $v=1\rightarrow 0$ $S(3)$ line] and near 4000 cm^{-1} (affecting particularly the Q lines). From experience, there is at least a $\pm$10% uncertainty due to systematic effects. This would mean about a $\pm$15% uncertainty in line ratios.

ii) *Absolute Values*

SOFTS spectra are usually normalized by using the observed continuum and an absolute flux for the object determined by some other means. In the case of AFGL 618, no absolute observations obtained close to the time of the infrared spectroscopy are known to the author. This is unfortunate as the source is known to be variable at a number of wavelengths (Gottlieb and Liller 1976; S. Kwok 1980, private communication), as well as in the H_2 lines (S. Beckwith 1981, private communication). Nevertheless, an earlier absolute measurement of an H_2 line intensity was used to normalize the relative line strengths in Table 1. On 1979 December 2, the $v=1\rightarrow 0$ $S(1)$ line was measured by Beckwith and DeNoyer (private communication) using a grating system (Beckwith *et al.* 1981). They found $F_{S(1)}=1.4\times10^{-12}$ ergs s^{-1} cm^{-2}. This compares with 0.5×10^{-12} ergs s^{-1} cm^{-2} measured by Beckwith, Persson, and Gatley (1978) a little over two years previously. A rough calibration can be also obtained from the broad-band 2 μm flux measured through the SOFTS at the time of observation and compared with standard sources. This gave $m_K=9.7\pm0.3$, which in turn gives $F_{S(1)}=1.1\pm0.3\times10^{-12}$ ergs cm^{-2} s^{-1}. Since this is in agreement with, but more uncertain than, the value measured by Beckwith and DeNoyer, their value will be used to define absolute flux levels.

III. ANALYSIS AND DISCUSSION

As the primary observational result, most of the analysis of AFGL 618 is based upon the H_2 line ratios. These may be heavily extinguished by the dusty material surrounding the region of emission. This should be corrected for, followed by a determination of the characteristics of the molecular excitation. The observation of the atomic hydrogen Bγ line flux can be used to estimate source extinction, but with a result strikingly different from that found for the H_2 lines. This difference is the primary contribution of these observations toward understanding the structure of the source (§ III*d*).

a) *Extinction*

i) *The* H_2 *Lines*

The molecular hydrogen line ratios may be used to find the extinction overlying the region of emission by making use of pairs of lines formed in the same upper level. The $S(J)$ lines are $J+2\rightarrow J$, $\Delta v=1$ transitions and the $Q(J)$ lines are $J\rightarrow J$, $\Delta v=1$ transitions. Therefore, the $S(0)$ line arises from the same upper level as $Q(2)$, the $S(1)$ from the same upper level as $Q(3)$, and so on. For unextinguished lines, the ratios of such pairs should simply equal ratios of the energy of the line multiplied by the Einstein A values. (All molecular parameters have been taken from Hollenbach and Shull 1977). If the ratios are different from this, the difference can be taken as due to differential extinction. With a known extinction law, the visual obscuration can be readily found from the line ratios.

Unfortunately, it is quite probable that AFGL 618, its circumnebular dust due to mass loss from a highly evolved star, would have an extinction law very different from the general interstellar medium. Therefore, no reliable estimate of the amount of dust attenuation can be made.

This situation is compounded in any case by the very small wavelength range ($\Delta\lambda/\lambda\sim0.15$) over which the differential extinction of the H_2 lines would be determined, followed by a large extrapolation into the visual.

For these two reasons *uncorrected* line ratios only are used in the subsequent analyses. This is not a major difficulty, however. In the first place, whatever the extinction law in AFGL 618, it almost certainly falls rapidly with increasing wavelength [the "normal" interstellar extinction decreases in the infrared as $\lambda^{-1.9}$ (Johnson 1968)]. This is a significant reduction in the effect of obscuration on line intensities. Second, although as noted above, the H_2 lines are quite close together in wavelength, this has the definite advantage of greatly reducing the effects of *differential* extinction. Therefore, ignoring the probable circumnebular extinction should allow an adequate first approximation to understanding the line emission. Residual effects of this ignorance are discussed in § III*b*.

Despite the near-certainty of nonnormal obscuration in AFGL 618, it is of interest nevertheless to estimate the visual extinction to the H_2 emission region under the restriction of "normal" absorption. In the infrared $A_\lambda = 0.4A_v/\lambda^{1.9}$ [μm] in the general interstellar medium. Four pairs of lines in Figure 1 [$v=1\rightarrow 0$ $S(0)$, $S(1)$, $S(2)$, $S(3)$, and their Q-line counterparts] give $A_v = 8 \pm 6$ mags. This will be shown to be far below that found for the Bγ emission.

ii) *The* Bγ *Line*

Table 1 has a value of $F_{\mathrm{B}\gamma} = 1.1 \times 10^{-13}$ ergs cm^{-2} s^{-1} using the same normalization as adopted for the H_2 lines. This value may be compared with the Balmer line intensities reported by Schmidt and Cohen (1981). Corrected for $A_v = 3.5$ mag of interstellar reddening (Calvet and Cohen 1978; Schmidt and Cohen), a total Hβ flux from the source was found to be $F_{\mathrm{H}\beta} = 2.4 \times 10^{-12}$ ergs cm^{-2} s^{-1}. This amount of extinction would, of course, have no effect on the observed Bγ flux. Assuming Menzel's case B, Hβ should be 37 times stronger than Bγ (Giles 1977; Osterbrock 1974). Under the assumption, then, of emission from the same region, the observed Bγ flux is about a factor of 2 larger than that predicted from the Schmidt and Cohen Hβ flux. This discrepancy is even larger for two reasons. First, the 8″ aperture of the SOFTS did not quite include all of the two lobes of the source. This is expected to be only a small factor, however. More significant, Schmidt and Cohen estimate that about half the total observed Hβ flux is radiation scattered toward Earth by dust in the lobes. Although the grain composition in AFGL 618 can only be guessed, it is a virtual certainty that the scattering at 2.2 μm is far below that in the visual. Therefore, the observed Bγ strength should be compared with that deduced only from the Hβ emission directly from the lobes. In this case, the observed Bγ line is over 3 times stronger than that expected on the basis of the Hβ line.

There are a number of possible explanations for this difference, particularly in a complex source like AFGL 618. Three seem likely. First, the source is a known variable and about a year passed between the visual observations of Schmidt and Cohen and the infrared spectra presented here. Second, the lobes may be dustier and clumpier than described by Schmidt and Cohen. A large amount of gas may be hidden behind thick clumps of dust and is only seen in emission at longer wavelengths. The visual line ratios would not be much affected by very thick dust and would lead to a low value for the obscuration. Exactly this effect has been suggested by Persson and Frogel (1974) for the young K3-50 and by Thronson and Harvey (1981) for the evolved HM Sge object.

A third possibility is related to the last: the gas dominating the Bγ emission may be the compact H II region that is obscured by the torus that surrounds the exciting star (Westbrook *et al.* 1975; Schmidt and Cohen 1981), but has been seen in the radio continuum (Wynn-Williams 1977; S. Kwok, private communication). If optically thin, the expected radio flux density may be predicted from the observed Bγ flux via

$$I_{\mathrm{ff}}\,[\mathrm{Jy}] = 10^{11} F_{\mathrm{B}\gamma}[\mathrm{ergs\ cm^{-2}\ s^{-1}}] \qquad (1)$$

(e.g., Tokunaga and Thompson 1979), where I_{ff} is the radio flux density. The equation is correct at 10 GHz and varies only very slowly with radio frequency. The observed Bγ line (Table 1) then predicts $I_{\mathrm{ff}} = 8$ mJy, subtracting the small amount of line flux expected to be contributed by the lobes (above). This is far below $I_{\mathrm{ff}} = 60$ mJy reported by Wynn-Williams in early 1977 and $I_{\mathrm{ff}} = 89$ mJy found more recently by Kwok, both at 15 GHz. The most obvious explanation for this is high circumnebular extinction around the dense H II region. The exact amount of absorption cannot be reliably estimated, again because of the unknown extinction law in the source. In the event that this should be the same as in the interstellar medium, the radio observation of Kwok and the Bγ flux in Table 1 would require 2.6 mags of extinction at 2.2 μm, or $A_v = 28$. The actual value for A_v would probably be much larger since the radio continuum emission is at least partially optically thick (Wynn-Williams 1977). Although this is an unreliable estimate for A_v, the important point to notice is that for any extinction law that varies as λ^{-n}, $n \sim 1-3$, the extinction deduced from the Bγ line is significantly larger than that found from the molecular hydrogen lines.

b) *Excitation*: *The Molecular Hydrogen Lines*

Two recent models have been suggested for excitation of molecular hydrogen: shock or collisional excitation (see, e.g., Kwan 1977; Hollenbach and Shull 1977) and ultraviolet pumping (Black and Dalgarno 1976). The latter mechanism has generally been found to predict H_2 line strengths in disagreement with observations, both in planetary nebulae (Smith, Larson, and Fink 1981) and in the BN-KL region (see, e.g., Hollenbach and Shull 1977). In particular, the UV-pumping model predicts $v=2\rightarrow 1$ lines to be stronger than actually observed. The same is true for AFGL 618 and only shock excitation will be considered in this paper.

In general terms, the source of the shock lies in some material overrunning a preexisting cloud of gas at a velocity difference of greater than ~ 5 km s^{-1}, below which CO emission can quench H_2 excitation, but less that ~ 25 km s^{-1}, where H_2 is collisionally destroyed (Kwan 1977). This simple description, therefore, seems to require at least two stages of mass loss in the precursor to an object like AFGL 618, and the velocity difference at the interface between the two stages to be in the range 5–25 km s^{-1}. These conditions are met by the planetary nebula formation of Kwok, Purton, and FitzGerald (1978), where a red giant loses mass at a high rate, but relatively low velocity until its core is exposed. Thereupon the outward expansion velocity greatly increases with the new, faster flow overrunning the neutral, extended material from the first period of mass loss. At the interface between the two flows a high density shell forms. It moves outward at between 10–40 km s^{-1} (depending upon input parameters) relative to the outer envelope. This velocity certainly is in the range necessary for H_2 excitation.

This model may be compared to the observations of AFGL 618 as the H_2 line strengths are sensitive to preshock density and shock velocity. In the following discussion, it is assumed that the H_2 emission is formed in a uniform region, is isothermal, and has a single characteristic shock velocity. This is clearly an oversimplification but is necessary at least in part because published models have not included the entire range of all possible source parameters. In the following, an attempt is made to estimate the preshock density, n_g, the shock velocity, V_s, and the H_2 rotation-vibration excitation temperature, T_{ex}.

To an adequate approximation, the H_2 line ratios are independent of n_g, depending mainly upon shock velocity (Shull and Hollenbach 1978). The results in Table 1 can therefore be used to estimate this velocity. Unfortunately, at $V_s \gtrsim 15$ km s^{-1} line ratios become quite insensitive to velocity (Hollenbach and Shull; Kwan 1977). However, the line ratios in AFGL 618 are consistent with those tabulated by Hollenbach and Shull for $V_s \sim 6$–10 km s^{-1}. Above this velocity the expected $v=2 \rightarrow 1$ $S(1)$ and $S(3)$ and $v=1 \rightarrow 0$ $Q(5)$ and $Q(7)$ lines would exceed the observed values (Table 1). Below $V_s = 5$ km s^{-1}, H_2 emission rapidly becomes very weak, making detection very difficult. It seems therefore reasonable to take the shock velocity to lie in the range 6 km $s^{-1} \lesssim V_s \lesssim 10$ km s^{-1}. Of course, it will be very much more desirable to actually measure the line width or shift with a spectrometer of suitable resolution rather than relying upon the more uncertain method of line ratios.

With the velocity estimated, the specific intensity of the $v=1 \rightarrow 0$ $S(1)$ line may be used to estimate the source density from the theoretical calculations presented in Figure 2 of Kwan (1977). For the 8″ beam used in these observations, $I_{S(1)} \geq 1.2 \times 10^{-3}$ ergs cm^{-2} s^{-1} sr^{-1} which indicates $n_g \gtrsim 10^5$–10^6 cm^{-3} for $5 \lesssim V_s \lesssim 10$ km s^{-1}. If the H_2 emission arises entirely within the small infrared source found by Westbrook *et al.*, n_g is about an order of magnitude greater.

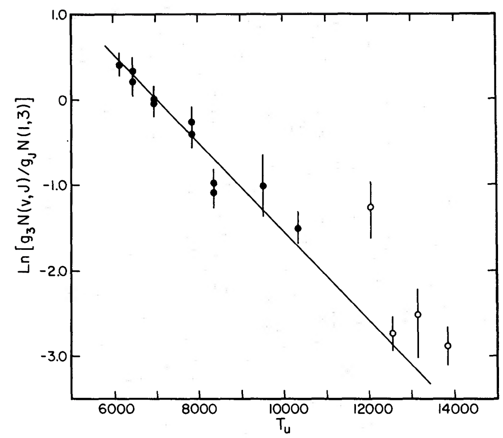

FIG. 2.—The relative population of $v=1$ and $v=2$ rotation levels plotted versus upper level temperature (see text). The points are shown with their 1 σ statistical errors combined quadratically with the estimated $\pm 15\%$ systematic uncertainty. The least-squares fit to the $v=1 \rightarrow 0$ lines is also shown. The $v=2 \rightarrow 1$ lines are shown as open circles.

With densities in this range, it is expected that the molecular hydrogen rotational level populations follow a Boltzmann distribution (Kwan 1977; Shulland Hollenbach 1978). The same distribution may also serve as a reasonable first approximation to the vibrational levels as well. Under this assumption, a level population, normalized to that of the upper level of the $v=1 \rightarrow 0$ $S(1)$ line, is

$$\frac{g_3 N(v,J)}{g_J N(1,3)} = \exp\left[-\frac{[E(v,J)-E(1,3)]}{kT_{ex}}\right], \quad (2)$$

where g_J is the statistical weight of the Jth rotational level, $N(v,J)$ is the population, $E(v,J)$ is the energy of the upper level, and k is Boltzmann's constant. The left side of equation (3) may be written in terms of known or observed quantities, viz.,

$$\frac{F_{v,J}\nu_3 A_3 g_3}{F_{1,3}\nu_J A_J g_J} = \frac{g_3 N(v,J)}{g_J N(1,3)}, \quad (3)$$

where F is the line flux and ν is its frequency. A plot of the natural log of equation (2), making use of equation (3) to find the relative population levels, is shown in Figure 2. The figure plots the temperature of the upper level of the transition, $T_u = E(v,J)/k$. The error bars on the points are the $\pm 15\%$ systematic uncertainty estimated in § II*b* for line ratios combined quadratically with the statistical uncertainties in Table 1.

From equation (2), a straight-line fit to the plotted points has a slope of $-0.625/T_{ex}$. A least-squares solution gives $T_{ex}=1950\pm200$ K using only the $v=1\rightarrow0$ points. The uncertainty is the formal result of using the errors shown in the figure. It may be too low, particularly considering the simplifying assumptions that are implicit in the use of equation (2).

An additional source of uncertainty was the use of line ratios not corrected for circumnebular extinction. This has already been argued to be largely unavoidable at this time because of the unknown extinction law in the source. It is, however, worth pointing out the likely effect that correcting for absorption would have. Simply in terms of number, changes in the relative intensities of the seven *Q* lines would have the greatest effect. Because they have about the same wavelength, they would change, relative to the $v=1\rightarrow0$ *S*(1) line, uniformly. In Figure 2 they would drop, but largely maintaining their straight-line orientation. The *S*(0) line point would also drop relative to that of *S*(1), if corrected for extinction, but the *S*(2) and *S*(3) lines would rise. The four *S* lines, then, would tend to give a higher temperature than found for the uncorrected ratios. Again, because of the low differential extinction at these wavelengths, this effect should be quite small. The estimate of 1950 K for the excitation temperature is probably quite good, even though the lines are uncorrected.

This value for T_{ex} is in the range expected theoretically for shock excitation of H_2 (e.g, Kwan 1977; Shull and Hollenbach 1978). Interestingly, it is not much different from that found for the extremely young BN–KL region (Gautier *et al.* 1976) and the compact planetary nebula NGC 7027 (Smith, Larson, and Fink 1981). That T_{ex} in three very different sources should range over only a few hundred degrees is not, in fact, too surprising. In the first place, equation (2) shows T_{ex} to be quite insensitive to the level population and, thus, the observed line intensities. Further, there is a sort of "thermostatting" effect in shock excitation that limits significant H_2 emission to a narrow range in shock velocities and, in turn, excitation temperatures. Kwan, for example, predicts a very steep falloff in the $v=1\rightarrow0$ *S*(1) line intensity for $V_s\lesssim10$ km s^{-1}. This makes such low velocity, and lower temperature, shocks less readily observable. Above $V_s=25$ km s^{-1}, the H_2 is almost totally destroyed and no 2 μm emission would be seen. There are therefore extremely effective constraints to keep H_2 excitation within relatively narrow limits.

The previous points notwithstanding, it is of some interest that there is good agreement with as simple an equation as equation (2) over a wide range in T_u. The physical conditions in AFGL 618 are likely to be very complex, and a single value for T_{ex} seems improbable. However, in the models of Kwan (1977), the structure of the shocked region is found to be quite narrow, characterized by a steep falloff in the density of emitting material. It may then be expected that a relatively small part of the source completely dominates the net emission from AFGL 618, and this small part is likewise characterized by a small range in excitation temperatures.

Figure 2 shows that a single T_{ex} appears to predict the level populations for the $v=2\rightarrow1$, as well as the $v=1\rightarrow0$ lines, at least within the uncertainties. The particle densities in the source are apparently high enough that thermodynamic equilibrium (TE) has been achieved in the region, at least up to the lower rotational levels of the $v=2$ state. The minimum value needed to obtain TE may be estimated by requiring that the rate of collisional transitions out of the upper state, $v=2$, be greater than that of spontaneous transition: $n_x\gamma_{21}^x\gtrsim A_{21}$, for transition between vibrational levels 1 and 2. This is somewhat more probable than transitions between levels 2 and 0. Here γ_{21}^x is the $2\rightarrow1$ transition rate for collisions between H_2 and species x, and n_x is its density.

The two most likely particles for de-excitation of the molecular are, of course, H_2 and H. Hollenbach and McKee (1979) gave values for γ_{21}^{H}, $\gamma_{21}^{H_2}$, and A_{21}. If the excitation temperature calculated above is equal to the gas kinetic temperature (as it would be in TE), then $n_H>6\times10^3$ cm^{-3} or $n_{H_2}>8\times10^5$ cm^{-3}. In practice, the densities must be rather larger than these minima, at least by a factor of ~5, to reach TE. This simple calculation emphasizes that atomic hydrogen is much more effective at H_2 excitation than is molecular hydrogen, and that destroying only a small fraction of the H_2 ($\sim1\%$) could rapidly change a non–TE situation into TE. These points have been discussed in more detail by Kwan (1977) and Hollenbach and McKee (1979).

It is worth noting that simply because Figure 2 is good evidence for TE between $v=1$ and $v=2$ populations, it does not necessarily follow that they are in TE with the $v=0$ level. Indeed, a similar calculation as above for transitions between the $v=0$ and $v=1$ levels, noting that the atomic parameters are somewhat uncertain, indicates that $n_H>3\times10^4$ cm^{-3} or $n_{H_2}>6\times10^5$ cm^{-3} is necessary for TE. Thus, significantly higher densities are required for TE if atomic hydrogen excitation is dominating. Of course, a complete detailed balance analysis is necessary to explore this type of problem.

c) *The Pure Rotation Lines and Mass of Shocked* H_2

Only the $v=1\rightarrow0$ and $v=2\rightarrow1$ lines have been observed in AFGL 618. To date, the important $v=0\rightarrow0$, pure rotation lines have been detected only in the BN–KL region of Orion (Beck, Lacy, and Geballe 1979; Beck *et al.* 1980; Knacke and Young 1980). It is natural that attention be concentrated on this source, but the well-understood structure and energetics of the proto-

TABLE 2

Rotational Line Intensities

Line	$\lambda(\mu m)$	$F_{0,J}/F_{1,3}$
$J=4\rightarrow2$ ...	12.3	0.01
$5\rightarrow3$ ...	9.7	0.1
$6\rightarrow4$ ...	8.0	0.05
$7\rightarrow5$ ...	6.9	0.3
$8\rightarrow6$ ...	6.1	0.1
$9\rightarrow7$ ...	5.5	0.4
$10\rightarrow8$ ...	5.0	0.1

planetary nebulae should also make them attractive targets for future H_2, $v=0\rightarrow0$ observations.

Making the assumption that the rotational and vibrational levels are in TE at $T_{ex}=1950$ K allows a straightforward estimate of the expected flux in individual pure rotation lines relative to that in the $v=1\rightarrow0$ $S(1)$ line, although such a calculation should be considered extremely rough. With the $v=0\rightarrow0$ line parameters taken from Aannestad (1973), the estimated line strengths are presented in Table 2 for the reasonably accessible 5–12 μm region. Most of the lines are seen to be ~0.1–0.3 of the strength of the $v=1\rightarrow0$ $S(1)$ line. This is well within the capabilities of the instruments operating in this wavelength region (e.g., Beck *et al.* 1980).

It is worth noting that in the BN–KL region it is the $J=4\rightarrow2$, 12.3 μm line on which observations have been concentrated. As Table 2 shows, this is the weakest line in this wavelength region for AFGL 618 (as it probably is for BN–KL). This is due both to the low statistical weight for its upper level, as well as a low Einstein A value. The advantage of this line is that it has the longest wavelength of the easily accessible mid-infrared lines and thus suffers less circumnebular extinction in a source like those in Orion. In particular, it is out of the deep 9.7 μm "silicate" absorption feature. AFGL 618, on the other hand, has no apparent 9.7 μm feature, and the infrared extinction is probably much lower than that found in BN–KL. To a large degree, this can compensate for the lower intensity of the H_2 lines in this source. This should make AFGL 618 and related objects interesting candidates for future $v=0\rightarrow0$ observations. Because most of the shocked molecular hydrogen ($\sim95\%$) occupies the $v=0$ state, these lines are of particular importance in understanding the H_2 shocked gas energetics.

In a manner similar to the calculation above, with the assumption of TE and an absolute $v=1\rightarrow0$ S(1) line intensity, the mass of shocked H_2 can be estimated. At a distance of 1 kpc, $M_{H_2}\sim10^{-4}\ M_\odot$. For comparison, this is about an order of magnitude less than that found by Smith, Larson, and Fink (1981) for NGC 7027. In both objects, this is a small fraction of the total gas mass in the source.

d) *Source Structure*

The visual structure of AFGL 618, along with suggested locations of the associated infrared source and H II region, has been described by Westbrook *et al.* (1975) and Schmidt and Cohen (1981). The observations reported here agree with their picture and contribute important details. Briefly, Westbrook *et al.* suggested that a hot, exciting star lies at the center of a dense, dusty compact H II region. At opposite poles of the source are two large reflection nebulae, giving the source its characteristic "double-lobed" appearance. It is suggested that the gas and dust close in about the exciting star is in the form of a toroid with the reflection nebula being illuminated through the openings at each end of the torus. The source of the circumstellar material has been mass loss from a late-type giant (§ III*e*). Schmidt and Cohen contribute details about the physical conditions in the lobes, noting the significant ionized gas within them.

Westbrook *et al.* found $A_v\approx3.5$ from the visual emission lines seen in the nebula. The continuum visual light is also highly polarized. The Bγ line was used to estimate $A_v\gtrsim28$. A natural explanation for the difference in the two results is the very low albedo in the infrared for commonly suggested grain materials (Aannestad 1975; Jones and Merrill 1976). At visual wavelengths, the dust albedo approaches ~0.5, but is essentially zero longward of about 1 μm. The Brackett line equivalents to the Balmer lines observed by Westbrook *et al.* are simply not reflected toward Earth from the lobes of AFGL 618. The $A_v\gtrsim28$ found by comparing the expected Bγ flux with that deduced from the radio observations must then refer to direct line-of-sight absorption to the compact H II region. This is the extinction through the torus of dust that surrounds the H II region and its exciting star.

If this is the case, it is not surprising that A_v found from the H_2 emission lines is smaller than that found for the Bγ line. Molecular hydrogen stands in danger of radiative or collisional dissociation if too close to the exciting star or its H II region. If emission from AFGL 618 can be thought of to arise from concentric rings about the exciting star, the H_2 emission may be expected to arise from outside the H II emission. This would keep the H_2 protected by a layer of dust and also might be the natural location for shock-excited emission to arise. In either case, looking at the source from the outside, the extinction to the dominant region of H_2 emission is less than the extinction to the H II region, as observed.

IV. SUMMARY

A 1.9–2.5 μm spectrum of the protoplanetary nebula AFGL 618 is presented. At least 11 members of the H_2, $v=1\rightarrow0$ series and two of the $v=2\rightarrow1$ series are detected. The observed ratios are in agreement with only a moderate amount of overlying extinction, perhaps $A_v \sim$ 10 mags, and a shock velocity of $\sim$10 km s^{-1}. The excitation temperature found for the $v=1$ level is 1950 K, similar to that found for other objects that show H_2 emission. The hydrogen Brackett γ line flux allowed an estimate of $A_v \gtrsim 28$ mags to the associated H II region. The fact that $A_v \sim 3.5$ was deduced from the visual line ratios is consistent with the idea that the exciting star in AFGL 618 is girdled by a ring or disk of dusty material, with reflection nebulae generated at opposite poles. The comparison of extinction found for the H_2 and H lines shows that the molecules are excited outside the ionized zone, in a region shielded from high intensity, direct stellar radiation. The observation and analysis discussed here is consistent with the view that AFGL 618 is an extremely young example of a protoplanetary nebula.

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