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DUST AROUND AFGL 2688, MOLECULAR SHIELDING, AND THE PRODUCTION OF CARBON CHAIN MOLECULES

M. JURA AND H. KROTO[1]
Department of Astronomy, University of California, Los Angeles
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ABSTRACT

The molecular, infrared, and optical maps of the evolved carbon star AFGL 2688 (the "Egg" Nebula) are all consistent with a model of a bipolar outflow of approximately 10^{-4} $M_\odot$ yr^{-1} that stopped as this object evolved beyond the asymptotic giant branch about 200 years ago. In order to explain the extended HC_7N emission around this star, we propose that carbon grains are collisionally fragmented as they supersonically stream through the circumstellar envelope.

Subject headings: nebulae: individual (AFGL 2688) — nebulae: internal motions — stars: circumstellar shells

I. INTRODUCTION

AFGL 2688 is a carbon-rich pre–planetary nebula star that displays a bipolar outflow (Ney *et al.* 1975; Zuckerman *et al.* 1976). It is probably approximately 1 kpc from the Sun, which implies that it has a luminosity near 2×10^4 $L_\odot$. Currently, it is an F star (Crampton, Cowley, and Humphreys 1975, indicating an effective temperature near 8000 K), but in the very recent past it most probably was a cool red giant on the asymptotic giant branch, at which time it was losing mass at $\sim 10^{-4}$ $M_\odot$ yr^{-1} (Jura 1983*b*; Knapp and Morris 1985; Morris 1980).

The physical and chemical properties of the material in the outflows from carbon-rich red giants are still not fully understood. Objects such as the nearest and best-studied mass-losing carbon star, IRC +10216, are known to have a very rich variety of molecules (Olofsson 1987) and a significant amount of large carbon-dust particles (Martin and Rogers 1987). However, the size and kinds of many of the carbon particles and molecules that are formed in the outflows are not known. Such information is critical for our understanding of the origin of interstellar and circumstellar grains, polycyclic aromatic hydrocarbon (PAH)–like particles (Léger, d'Hendecourt, and Boccara 1987; Omont 1986), and other complex carbon species such as C_{60} and related carbon-cage molecules (Kroto 1988).

In the simplest picture, the outflow from a mass-losing cool carbon-rich star can be divided into three zones (see, for example, Lafont, Lucas, and Omont 1982; Glassgold *et al.* 1987). There is an inner zone ($r < 10^{14}$ or 10^{15} cm, depending upon the mass-loss rate), dominated by three-body reactions, where grains and complex particles are synthesized. In this region matter is accelerated to its terminal outflow velocity, which characteristically is 15 km s^{-1}, and the evolving composition tends to "freeze out" as it flows outward and the pressure drops. Farther from the star (10^{14}–10^{17} cm), there is a zone of lower density where two-body chemical reactions dominate the processing of the material. Finally, far from the star ($> 10^{16}$ or $> 10^{17}$ cm), the collision time between gas particles is long compared with the dynamic outflow time. In this outermost region, photoprocessing and photodissociation by the ambient interstellar ultraviolet radiation field are the dominant processes. Particularly abundant molecules, such as CO and H_2, can be self-shielding and need not be protected by dust (Morris and Jura 1983; Mamon, Glassgold, and Huggins 1988).

Certain limited aspects of the grain formation and processing in the outflows from red giants can be modeled in a satisfactory fashion. For example, there is good agreement between observations and models for those oxygen-rich stars where dust particles accrete solid water ice mantles onto their surfaces (Jura and Morris 1985).

Nguyen-Q-Rieu, Winnberg, and Bujarrabal (1986), using the VLA, discovered that HC_7N around AFGL 2688 extends as much as 20″ from the star. In the same telescope beam, the HC_7N shows a different distribution and is significantly more extended than that of NH_3. As discussed below, the NH_3 probably maps out the region where gas is protected by dust from the ambient interstellar ultraviolet radiation. The HC_7N is not as extended as the CO (Heiligman *et al.* 1986; Kawabe *et al.* 1987), which, however, is self-shielded. Because the observed HC_7N is found so far from the star where we expect this molecule to be rapidly photodissociated, we presume that it is being synthesized relatively rapidly in the outer circumstellar envelope. One of our goals is to describe a model for this synthesis.

There have been a number of models for the gas-phase synthesis of the polyynes such as HC_7N in interstellar and circumstellar environments (Freeman and Millar 1983; Kroto *et al.* 1987; Leung, Herbst, and Huebner 1984; Mitchell, Huntress, and Prasad 1979; Nejad and Millar 1987; Schiff and Bohme 1979; Stahler 1984). These models may be valid for the formation of the simpler polyynes such as HC_3N in IRC +10216 (Bieging and Nguyen-Q-Rieu 1988*b*). However, these calculations seem unlikely to be able to explain the spatially extended HC_7N around AFGL 2688. The interferometric map obtained with the VLA by Nguyen-Q-Rieu, Winnberg, and Bujarrabal (1986) shows the highest concentrations of HC_7N well away from the regions where we expect the highest gas densities and where the most complex gas-phase chemistry might occur. Instead, the HC_7N is mainly concentrated in the outer zones ($r > 10^{17}$ cm). The most natural explanation that we can find for the observed morphology of the HC_7N is the fragmentation of larger carbon-bearing particles.

[1] Also School of Chemistry and Molecular Sciences, University of Sussex.

In this paper we synthesize data acquired by many different techniques to describe the dust around AFGL 2688 and some of its consequences. Infrared data are used to infer the total dust-loss rate and the inner zone of the dust cocoon. Previously, the optical data have been used to determine the angular distribution of the dust around this star. Maps of the molecules can be used to infer the penetration from the interstellar medium of ultraviolet photons that photodissociate these species. In § II we describe the photodissociation of molecules in the outflow from AFGL 2688. In § III we describe our model for the synthesis of the HC_7N, while in § IV we describe some implications of our model. In § V we present a summary. In an Appendix we discuss recently obtained mid-infrared maps of AFGL 2688, and we use our model to argue that the intense mass-loss phase from this star ceased about 200 years ago, at which time we presume that it evolved past the asymptotic giant branch.

II. PHOTODISSOCIATION OF NH_3, HCN, AND HC_7N

Consider now the anisotropic outflow from AFGL 2688. Let $\tau(\theta', \phi')$ denote the optical depth measured to infinity in the (θ', ϕ') direction at any location within the circumstellar envelope. If I_0 denotes the photodissociation rate of a molecule in the ambient interstellar medium, then, after averaging over all possible paths by which interstellar photons may penetrate into the molecular region, we can write for the net photodissociation rate, I,

$$I = I_0(4\pi)^{-1} \int \exp\left[-\tau(\theta', \phi')\right] d\omega' . \quad (1)$$

In equation (1), $d\omega'$ is the usual element of solid angle. For an anisotropic outflow, equation (1) can be very complex to solve. As a first approximation, we adopt an "average" effective optical depth, $\langle\tau\rangle$, which is simply the opacity measured in the radial direction to infinity (Jura 1983*b*). Therefore we write

$$I = I_0 \exp\left(-\langle\tau\rangle\right), \quad (2)$$

$$\langle\tau\rangle = \chi \frac{dM}{dt}(\theta)(4\pi r v)^{-1} . \quad (3)$$

In equation (3), χ is the opacity ($cm^2\ g^{-1}$) of the mixture of dust and gas together, r is the distance from the central star, and v is the gas outflow velocity. We write $dM/dt(\theta)$ for the mass-loss rate in the direction θ, the angle between the plane of symmetry and the radial direction.

In general, we expect that a molecule is photodissociated when the rate for this process is comparable to the dynamical flow time, r/v (Jura and Morris 1981; Huggins and Glassgold 1982). Close to a star with a large amount of dust, the time for photodissociation, I^{-1}, is much longer than the characteristic flow time. Far from the star, the reverse is true.

Yusef-Zadeh, Morris, and White (1984) have made a very detailed model for the spatial distribution of the dust around AFGL 2688. As a first approximation to the results in their Figure 2, we write

$$\frac{dM}{dt}(\theta) = M_0(1 - \sin\theta) . \quad (4)$$

For normalization, we require

$$\frac{dM}{dt} = \int \frac{dM}{dt}(\theta) \cos\theta \, d\theta . \quad (5)$$

In equation (4), $M_0 = 2.9 \times 10^{20}$ g s^{-1} if the total dust-loss rate is $2.3 \times 10^{-6}\ M_\odot\ yr^{-1}$ (Kleinmann *et al.* 1978; Sopka *et al.* 1985). In Figure 1 we compare the relative angular distribution of the dust given by equation (4) with the more detailed model of Yusef-Zadeh, Morris, and White (1984).

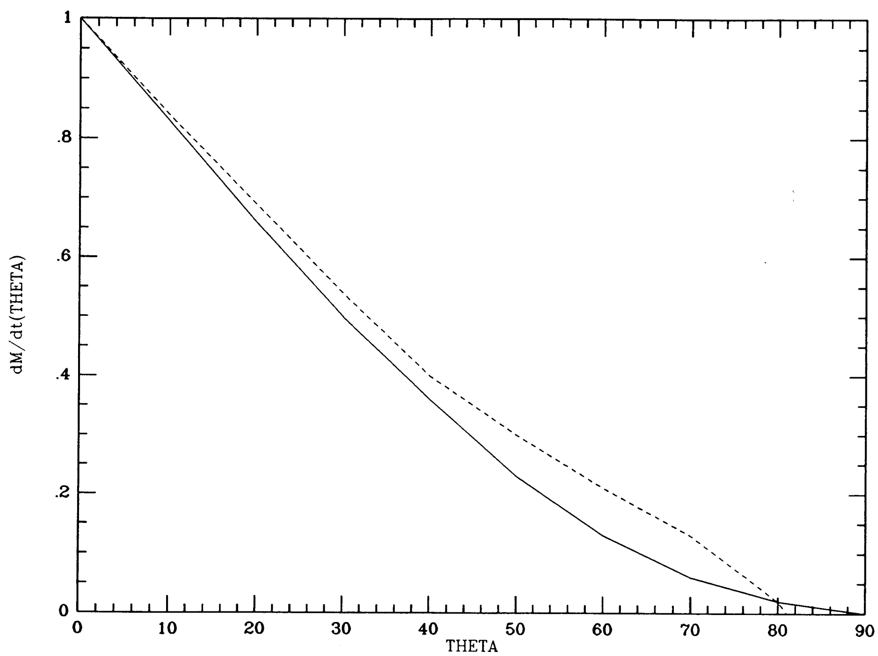

FIG. 1.—Plot of the theoretical angular distribution of dust around the equatorial plane of the outflow from AFGL 2688 in terms of θ, the angle measured from the plane. The dashed line is the detailed model of Yusef-Zadeh, Morris, and White (1984), while the solid line is our simple fit to that more detailed model.

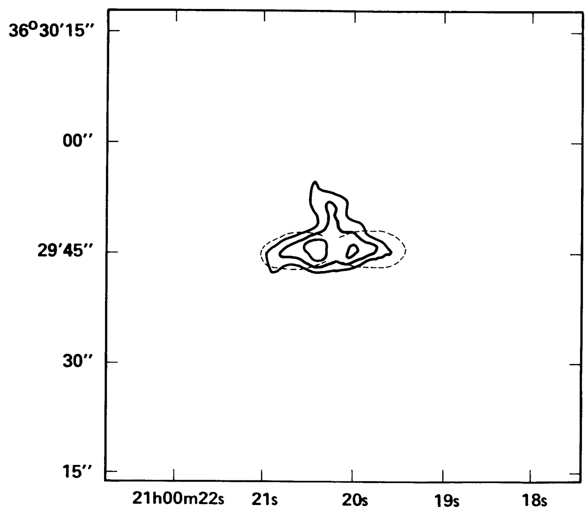

FIG. 2a

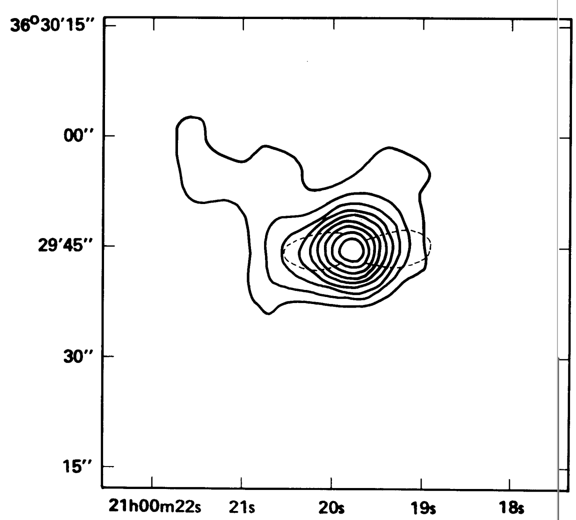

FIG. 2b

FIG. 2.—(*a*) Plot of the observed contours of NH_3 emission (Nguyen-Q-Rieu, Winnberg and Bujarrabal 1986) obtained with a 4″.3 × 3″.4 VLA beam (*solid lines*) compared with the boundaries calculated for a slice through the nebula in the plane of the sky outside of which the NH_3 is quickly photodissociated (*dotted lines*). In all our models we assume that the inclination of the equatorial plane to the line of sight is 0°, rather than 16° as proposed by Yusef-Zadeh *et al.* (1984). The model is cut off for $\theta > 60°$ because of the deep penetration of the interstellar ultraviolet photons. (*b*) Plot of the observed contours of HCN emission (Bieging and Nguyen-Q-Rieu 1988) obtained with a 4″.9 × 4″.9 beam at Hat Creek compared with the boundaries calculated for a slice through the nebula in the plane of the sky outside of which the HCN is rapidly photodissociated (*dotted lines*).

We can use this model for the dust distribution around AFGL 2688 to compute the size and shape of the photodissociation region. The infrared emissivity of the carbon grains varies approximately as ν^{+1} (Sopka *et al.* 1985; Jura 1986), and, at least for IRC +10216, it is possible to extrapolate this power law from the far-infrared to optical and ultraviolet wavelengths (Jura 1983*a*; Le Bertre 1987, 1988). Since we assume an opacity of the grains of 20 $cm^2\ g^{-1}$ at 400 μm, the ultraviolet opacity of the dust is $6 \times 10^4\ cm^2\ g^{-1}$.

We now compare this model for photodissociation with the data for the two best-studied molecules for which the calculations should apply: NH_3 and HCN. In the unattenuated interstellar medium, the rate for the photodissociation of NH_3 is $9.9 \times 10^{-10}\ s^{-1}$ (Lee 1984). Using an outflow velocity of 19 km s^{-1} and a distance to this star of 1 kpc, we find from equations (2), (3), and (4) the location where the rate of photodissociation of NH_3 equals the dynamic flow time. The results for a slice through the nebula in the plane of the sky, perpendicular to the line of sight, are shown in Figure 2*a* and are compared with the observed map of this molecule (Nguyen-Q-Rieu, Winnberg, and Bujarrabal 1986). The success of our model gives independent confirmation that we have a reasonably good understanding of the opacity and spatial distribution of the dust around this star.

In Figure 2*b* we compare a similar model for the distribution of the HCN around AFGL 2688, essentially the same as that for the NH_3, and compare it with observations (Bieging and Nguyen-Q-Rieu 1988*a*). We use a rate for photodissociation of HCN of $1.3 \times 10^{-9}\ s^{-1}$ (Lee 1984), which is only slightly higher than the corresponding rate for photodissociation of NH_3. With the exception of a "tongue" of emission in the north, and perhaps within the uncertainties caused by the beam size, the HCN map agrees roughly with the model. However, the HCN appears to be more extended than the NH_3. It is possible that, as we propose below for the HC_7N, there may be some chemical synthesis of HCN in the outflow from AFGL 2688 in addition to the molecules that are "frozen out" close to the star.

The maps of the H_2 and CO emission from AFGL 2688 are very different from those of HCN and NH_3. The H_2 emission is found to be mostly perpendicular to the equatorial plane of the system (Beckwith, Beck, and Gatley 1984), and we discuss its morphology in § IV. The CO is self-shielded.

In further contrast to the maps of NH_3 and HCN, the HC_7N, although it is not self-shielding and although the data are acquired with a larger beam than for the NH_3, is much more extended than we would expect on the basis of a model where it is simply photodissociated once it merges from the dusty environment of the inner circumstellar envelope. It appears that there is some production of HC_7N in the outer region ($r > 10^{17}$ cm) from this star. In the next section we discuss a production mechanism.

III. THE SYNTHESIS OF HC_7N AND OTHER CARBON CHAINS

In the map obtained by Nguyen-Q-Rieu, Winnberg and Bujarrabal (1986), the HC_7N is detected up to 20″ from the star, and it is concentrated neither toward the star nor in the dense equatorial plane where other species, such as NH_3, are mostly found. Instead, at least to the north of the star, the HC_7N may map out an extension of the high-velocity gas and reflection nebulosity that has been studied with H_2 and CO (Beckwith, Beck, and Gatley 1984; Kawabe *et al.* 1987). According to Truong-Bach, Graham, and Nguyen-Q-Rieu (1988), if a spherically symmetric mass-loss model is applied to analyze the abundance of HC_7N around AFGL 2688, the HC_7N loss rate from the central star would be 10^{-} (by number) of that by H_2.

In the outflow of material from a star, we know that carbon is present both in CO and in dust grains. The CO is observed to survive well beyond the zone where the HC_7N is found and in any case there is no obvious chemical pathway to convert CO into HC_7N. More likely, the observed extended emission of HC_7N is the consequence of the breakdown or fragmentation of grains or other larger carbon-bearing species. A similar model may be appropriate for the interstellar polyynes (Duley and Williams 1984).

Because grains in a circumstellar envelope are subject to an intense, anisotropic radiation field, they supersonically stream outward through the gas. The drift velocity of the grains through the gas, v_d, can be written (Kwan and Linke 1982) as

$$v_d = [Lv_t\langle Q\rangle/(c\,dM/dt)]^{1/2}\,. \qquad (6)$$

In expression (6), v_t is the outflow velocity of the gas, and $\langle Q\rangle$ is the ratio of the momentum transfer to the geometric cross section of the grains (see, for example, Spitzer 1978), averaged over the incident radiation field. For small grains, $\langle Q\rangle$ varies directly as the grain radius, r_{gr}. For an object like IRC +10216, most of the radiation from the central star is reprocessed into the infrared by the circumstellar dust grains. As a result, $\langle Q\rangle$ for grains of radius 0.1 μm might be 0.04, and the streaming velocity is on the order of 2 km s^{-1} (Kwan and Linke 1982). However, in the case of AFGL 2688, at least near the bipolar lobes, the optical depth is sufficiently small that the grains are directly exposed to the optical radiation from the central star. From analysis of the observed reflection nebulosity, we know that the grains are comparable in size to the optical light; typically, the grain radius is $\sim 10^{-5}$ cm (Schmidt, Angel, and Beaver 1978). When illuminated by optical rather than infrared light, the value for $\langle Q\rangle$ for these grains is ~ 1, and the grains can stream more rapidly through the gas. Also, at the poles there is less material, so the drag resistance is less.

The rapidly streaming grains collide with one another, and during these grain-grain collisions they may fragment. We hypothesize that the carbon grains fragment into a whole range of possible carbon species, including chains and cages. The HC_7N is relatively easily detectable and acts as a sensitive signpost for the grain destruction process.

To be more quantitative, we assume that the total value of Q is a function of angle arround the star and that $Q(\theta)$ can be written as

$$Q(a, \lambda, \theta) = Q(a, \lambda)_{ir} + \exp\,[-\tau_{neb}(\theta)]Q_{vis}(a, \lambda)\,, \qquad (7)$$

where a is the radius of a spherical grain and (7), Q_{ir} is the value of Q in the infrared, and Q_{vis} is the value of Q at visual wavelengths. Following Yusef-Zadeh, Morris, and White (1984), we adopt $\tau_{neb} = 11$ in the equatorial plane of the outflow. From equation (4), we write

$$\tau_{neb} = 11(1 - \sin\theta)\,. \qquad (8)$$

With equations (6), (7), and (8), we can compute the drift velocity of the grains through the gas as a function of angle measured from the equatorial plane of the outflow. In the Appendix we discuss how we use this value of τ_{neb} to derive the duration of the current F star phase of the star's evolution.

From equations (4)–(9), we can derive the supersonic drift velocity as a function of latitude measured from the disk with the assumptions of a luminosity of $2 \times 10^4\ L_\odot$, a mass-loss rate of $10^{-4}\ M_\odot$ yr^{-1}, and a gas outflow speed of 19 km s^{-1}. The results are displayed in Figure 3 for grains of radius 0.01 μm and 0.1 μm. We take $Q_{ir} = 0.004$ ($a = 0.01$ μm) and $Q_{ir} = 0.04$ ($a = 0.1$ μm) (see Kwan and Linke 1982), while we take $Q_{vis} = 0.2$ ($a = 0.01$ μm) and $Q_{vis} = 1.0$ ($a = 0.1$ μm). The rapid rise in the outflow velocity at high latitude is a consequence of both lower gas resistance and a greater radiative driving force. The effect of grain size on the outflow velocity is also displayed.

Let dN_{gr}/dt denote the loss rate by number of grains from the central star. If we assume that the grains are typically 10^{-5} cm in radius, that they are composed of carbon with a specific density of 3 g cm^{-3}, and that the dust-loss rate is 2.3×10^{-6}

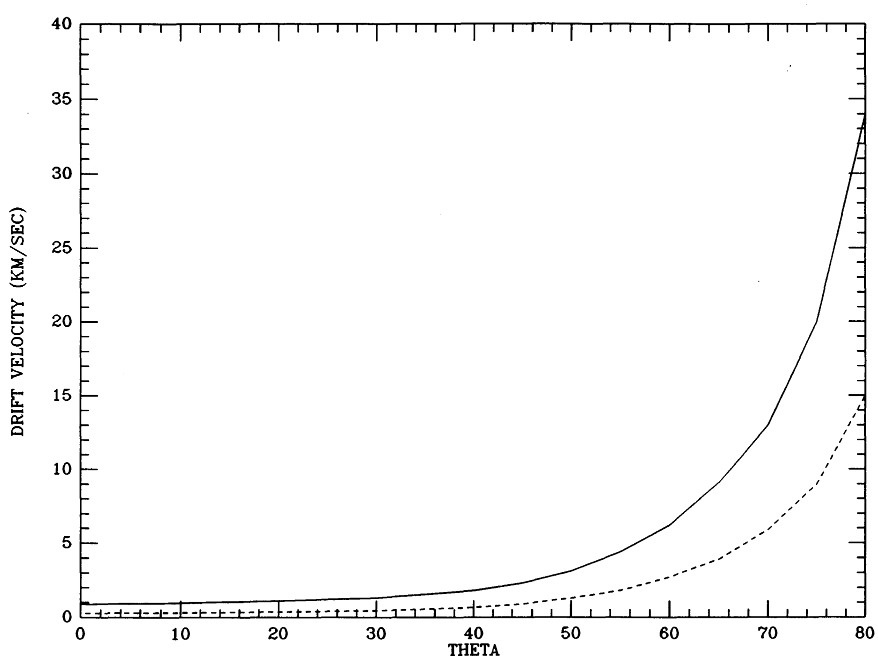

FIG. 3.—Grain drift velocity vs. latitude for the parameters given in the text. The results are shown for a grain of radius 0.01 μm (*dashed curve*) and 0.1 μm (*solid curve*).

$M_\odot$ yr^{-1}, then

$$dN_{gr}/dt = 2.3 \times 10^{34}(1 - \sin\theta)\ s^{-1} . \quad (9)$$

In order to reproduce the inferred dust distribution (eq. [4] or Fig. 1), we assume that all the grains have the same outward flow velocity. (Alternatively, we could assume an isotropic outflow with an anisotropic velocity field to reproduce the mass distribution in Fig. 1.) This assumption is not valid because the total outward flow velocity, the sum of the gas velocity plus the streaming velocity, is dependent upon angle. Nevertheless, since typically the grain streaming velocity is appreciably smaller than the gas outflow velocity, the errors that this assumption introduces are small compared with the many other uncertainties in our treatment. We assume, for the sake of computing the rate of grain-grain collisions, that

$$n_{gr} = \left[\frac{dN_{gr}}{dt}(\theta)\right] \Big/ (4\pi v_{tot} r^2) . \quad (10)$$

We take $v_{tot} = v_t + v_d = 22$ km s^{-1} in order to be consistent with the value of the velocity used to derive the dust mass-loss rate by Sopka *et al.* (1985).

The rate R of binary collisions between grains is given by

$$R = n_{gr}^2 \sigma_{gr} v_d . \quad (11)$$

In equation (11) we assume that the grains collide with one another at the supersonic drift velocity. We ignore the complication that particles of the same size have the same supersonic drift velocity and only collide with each other quite rarely. Instead, because of the size variation of the effective cross section, which is denoted by $\langle Q \rangle$, we expect that the large particles move more rapidly than the small particles, and with a range of particles sizes the rate of grain-grain collisions is given by equation (11).

As discussed for interstellar grains, the products of grain-grain collisions are not known (Duley and Williams 1984; Omont 1986; McKee *et al.* 1987; Seab 1987; Tielens *et al.* 1987). Although quite uncertain, we suppose that the binding energy of a carbon atom onto the grain is at least 2 eV. If the grains are primarily composed of carbon, then we require collision speeds of at least 6 km s^{-1} in order to have enough kinetic energy per atom to fragment the grain. This threshold speed is very uncertain.

In the outer envelope we expect that the rate of production of HC_7N, $R(HC_7N)$, is given (for regions with $v_d > 6$ km s^{-1}) by

$$R(HC_7N) = y(HC_7N) n_{gr}^2(\theta) \sigma_{gr} v_d(\theta) . \quad (12)$$

In equation (12), $y(HC_7N)$ is the number of HC_7N molecules that are ultimately produced following every grain-grain collision. As a first approximation, we assume that following a grain-grain collision, 0.03 of all the carbon atoms contained within a grain ultimately lead to the production of an HC_7N molecule and that $y(HC_7N)$ is independent of the collision speed. This yield is arbitrarily chosen and ultimately must be justified by experiment or more detailed theory. If 0.03 of all the carbon goes into the form of HC_7N, and since we assume 6×10^8 carbon atoms in each grain of radius 10^{-5} cm, we expect that $y(HC_7N) = 3 \times 10^6$. It is possible that intermediate species are formed, perhaps longer carbon chains, before HC_7N ultimately is synthesized.

Let $I(HC_7N)$ denote the rate for photodissociation of HC_7N in the ambient interstellar medium. We expect the time to reach chemical equilibrium is short compared to the flow time, and that

$$n(HC_7N) = R(HC_7N)/I(HC_7N) . \quad (13)$$

The value of $I(HC_7N)$ is unknown. For HCN the rate of photodissociation is 10^{-9} s^{-1} (Lee 1984), and we assume that the corresponding rate for photodissociation of HC_7N, which we imagine to be a more stable molecule because it is larger with more internal modes of energy storage (see Léger *et al.* 1989), is an order of magnitude smaller, or 10^{-10} s^{-1}.

Around AFGL 2688, Nguyen-Q-Rieu, Winnberg, and Bujarrabal (1986) estimate an average column density of HC_7N of 4×10^{14} cm^{-2}. We display in Figure 4 the contours in the slice of the nebula in the plane of the sky perpendicular to the line of sight where the HC_7N density equals 10^{-4} cm^{-3}. Because we are observing at distances $> 10^{17}$ cm from the star, this density results in about the minimum column density that can be detected. We expect the HC_7N to be concentrated in two bipolar, nearly hollow cones that are oriented perpendicular to the disk of the outflow. There is no HC_7N in the disk of the outflow because the grain drift velocity in this region is only about 2 km s^{-1}, well below the critical collision speed of 6 km s^{-1} that we suggest is required for grains to shatter. There is little HC_7N at the poles of the outflow because there is little matter. Given the large beam that was used to measure the contours in Figure 4, the agreement between the theory and observations is reasonable. However, we cannot rule out the possibility that there are additional chemical pathways for the synthesis of HC_7N in addition to that from grain-grain collisions.

From equation (13), we would predict a strong concentration of HC_7N toward the central star, contrary to observations. However, in applying equation (13), we assume that the mass loss has been constant with time; this approximation is probably not valid. Currently, AFGL 2688 is an F star (Crampton, Cowley, and Humphreys 1975), and in the Appendix we argue that it stopped losing mass ~200 years ago. Because the mass outflow rate and the composition, size, and

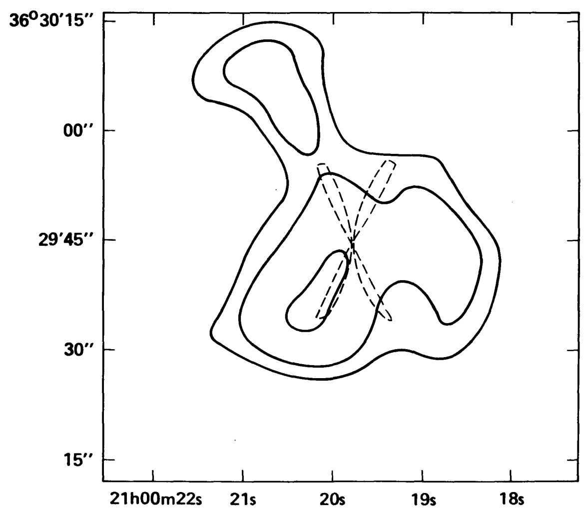

FIG. 4.—Plot of the observed contours of HC_7N emission (Nguyen-Q-Rieu 1986) obtained with 12″.1 × 10″.7 resolution compared with the model contour in a slice through the nebula in the plane of the sky perpendicular to the line of sight (*dashed line*) where the computed density of this molecule equals 10^{-4} cm^{-3}.

spatial distribution of the dust grains may have varied substantially with time, it is quite possible that the HC_7N is preferentially produced in what are currently the outer regions of the circumstellar envelope.

IV. IMPLICATIONS

Beckwith, Beck, and Gatley (1984) have observed extended H_2 emission in the $v = 1$–0 $S(1)$ line at 2.1 μm from AFGL 2688. They argue that this emission can by produced by a column density of 1.5×10^{18} cm^{-2} of hot ($T \sim 2000$ K) gas in the circumstellar envelope around AFGL 2688, and they suggest that this hot gas is produced by shock waves. Here we propose an alternative model for the observed emission. According to Jura, Kahane, and Omont (1988), once the supersonic grain streaming velocity is in excess of 10 km s^{-1}, the gas temperature in the circumstellar envelope can rise to be greater than 1000 K (see their eqs. [2]–[4] and their Fig. 5), depending upon a number of physical conditions. This hot gas can produce H_2 emission by collisional excitation. According to our Figure 3, we expect that the streaming velocity is greater than 10 km s^{-1} for $\theta > 70°$ or $\theta > 75°$, depending upon the grain size. At 7″ from the star, near the peak of the H_2 emission, the column of gas through the cone which lies in the region $75° < \theta < 90°$, roughly the region where we presume the gas to be warm enough to emit a significant number of H_2 photons, is about 4×10^{18} cm^{-2}, while the observed column of hot gas is about 1.5×10^{18} cm^{-2} (Beckwith, Beck, and Gatley 1984). Therefore, it is possible that an appreciable fraction of the observed H_2 emission results from hot gas created by rapid grain streaming.

This model predicts that the H_2 emission should be concentrated in a narrow cone perpendicular to the equatorial disk as is observed (Beckwith, Beck, and Gatley 1984). The H_2 observed emission is displaced from the central star by at least 5″ in either bipolar lobe, which corresponds to a distance of 7.5×10^{16} cm. For a gas outflow velocity of 19 km s^{-1} and an average streaming velocity in the cone defining the hot gas in the bipolar flow of perhaps 25 km s^{-1} (see our Fig. 3), the total speed of the grains perpendicular to the disk is 44 km s^{-1}. At this speed, the grains would travel 3×10^{16} cm in the 200 yr we estimate in the Appendix for the time elapsed since this star was a red giant. This predicted distance for the region where the hot gas may be found is approximately half of the minimum distance from the star where the hot H_2 is observed. Although this model does not reproduce the weak H_2 emission detected in the equatorial plane of AFGL 2688 (Gatley, DePoy, and Fowler 1988; Smith *et al.* 1988), given the many uncertainties in these calculations, it seems this model is promising for explaining the H_2 emission in the lobes of this object.

We predict that there may be a significant destruction of carbon particles in the outflows from red giants once rapid winds with grain drift velocities greater than 6 km s^{-1} are established. In models for the evolution from a red giant to a planetary nebula (Kwok 1982), such a rapid wind from the hot central star impinges upon the cold, slower wind left over from the red giant phase. The current interpretation of the infrared data of planetary nebulae is that the older objects show lower dust-to-gas ratios than do the younger, more compact ones (Natta and Panagia 1981; Pottasch *et al.* 1984). Our model for destruction of carbon particles in grain-grain collisions is qualitatively consistent with this result. The possible detection of C_{60} toward AFGL 2688 (Somerville and Bellis 1989) should be pursued in other carbon-rich objects.

Pringle (1989) has proposed that a massive disk left over from the star formation phase surrounds AFGL 2688. One difficulty with the model is that Pringle (1989) presumes that the star is currently 8 $M_\odot$, a mass that is about an order of magnitude larger than the usual value for a post–asymptotic giant branch star (Iben and Renzini 1983). Another problem is that the spectral line profiles of the circumstellar molecules are more consistent with an outflow than a disk (Morris 1980). Also, the chemical composition of the outflow is carbon-rich; a disk formed directly from the interstellar medium would presumably be oxygen-rich. Finally, the disk proposed by Pringle (1989) is oriented east-west, but the HC_7N extends north-south, so that even if this proposed disk is real, it does not bear any obvious relationship to this observed molecule.

V. SUMMARY

The molecular, infrared, and optical maps of AFGL 2688 can be reproduced with a model of a bipolar outflow where the mass loss stopped about 200 years ago. We suggest that the recent outflow from the carbon-rich mass-losing star AFGL 2688 contains a large number of fragile carbon particles. Particularly in the bipolar lobes, these grains are driven at high supersonic speeds through the gas, and when they collide with each other they fragment. We hypothesize that HC_7N and other carbon chain species are a significant product of these grain-grain collisions. The rapid supersonic streaming of the grains may produce high gas temperatures which lead to other consequences, such as H_2 emission.

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APPENDIX

MODEL FOR THE EXTENDED 10 MICRON EMISSION

Jaye *et al.* (1989) have reported mid-infrared (8.6–12.4 μm) maps of AFGL 2688 with a FWHM of 1″.9 in declination and 1″.5 in right ascension. Ney *et al.* (1975) also report a larger north-south 12.5 μm size (1″.5) compared with its measured east-west dimension (1″). If the emissivity of the grains varies as ν^{+1}, the derived color temperature is 210 ± 20 K. Jaye *et al.* (1989) find this result "unexpected" because the infrared emission is not concentrated in the disk of the bipolar outflow where most of the dust is located. Also, according to Sopka *et al.* (1985), the temperature of the dust grains at 1″ from AFGL 2688 should be 120 K, much less than the observed value. Here we note that their data are consistent with our model for the circumstellar envelope because the dust in the bipolar lobes is much warmer than the dust in the disk of the outflow.

Since AFGL 2688 is currently an F star, it is natural to imagine that the mass-loss rate has dropped dramatically from the time when the star was a cool red giant. We can estimate when the mass loss essentially stopped by the following argument. Let r_{in} denote the inner boundary of the dust distribution. If τ_{neb} denotes the total optical depth through the circumstellar envelope, we may write, from equation (4),

$$r_{in} = \frac{\chi}{4\pi v \tau} \frac{dM}{dt} .$$

With an emissivity that varies as ν^{+1}, we find at 5500 Å that the opacity is 1.5×10^4 cm^2 g^{-1}. Since the total optical depth in the equatorial plane is set equal to 11 in order to reproduce the optical map of the nebula (Yusef-Zadeh, Morris, and White 1984) and since the outflow speed (gas flow velocity plus streaming velocity) of the dust grains in the equatorial plane is 22 km s^{-1}, using the dust mass-loss rate given by equation (5), we find that $r_{in} = 1.4 \times 10^{16}$ cm. At a distance to the star of 1 kpc, this corresponds to an angular radius of the inner dust region of 0.″93, or an angular diameter of 1.″8. By projection, some of the dust at r_{in} apparently lies very close to the star in the sky; we predict an angular diameter of the infrared emission close to but slightly smaller than this value of 1.″8, in agreement with the measurement by Jaye *et al.* (1989) of 1.″5. At 22 km s^{-1}, it would take the dust 200 years to flow to r_{in}, and we presume that this is approximately the time when the star evolved from being a mass-losing red giant to its current hotter phase with a much lower mass-loss rate. Such a time scale is consistent with theoretical models for post–asymptotic giant branch evolution (Iben and Renzini 1983).

The temperature of the dust around AFGL 2688 depends upon the spectrum of the illuminating radiation. If the dust is heated by the same spectral distribution of energy that we observe at Earth, we expect a grain temperature at 1″ from the star of 120 K (Sopka *et al.* 1985). However, along the bipolar lobes there is much less dust, and we expect that the spectrum of the illuminating radiation will be similar to that of an F star rather than the spectrum observed at Earth, which peaks in the infrared. If the emission of the grains varies as ν^{+1}, and if we assume that the star has radius R_* and radiates like a blackbody of effective temperature T_*, then in the absence of intervening dust, we expect a dust temperature, T_d, at a distance D from the star of

$$T_d = T_*(R_*/4D)^{2/5} .$$

Since AFGL 2688 is currently an F star ($T_* = 8000$ K) with a luminosity of $2 \times 10^4 L_\odot$, we take $R_* = 5 \times 10^{12}$ cm. For a distance of 1 kpc, 1″ corresponds to 1.5×10^{16} cm, and therefore $T_d = 190$ K. This predicted temperature is consistent with the value observed by Jaye *et al.* (1989) of 210 ± 20 K.

A full treatment of the radiative transfer in the envelope around AFGL 2688 is beyond the scope of this paper (see Yusef-Zadeh, Morris, and White 1984). However, we expect the dust temperature to decrease in the plane of the outflow much more rapidly as a function of distance from the star than in the equatorial poles. At least qualitatively, we can understand why the infrared emission in the bipolar lobes is more extended than in the equatorial disk. Also, because the emision at 10 μm from 190 K grains is so much greater than from 120 K grains, it is not surprising that the 10 μm flux from the bipolar lobes is comparable to the flux from the equatorial disk even though there are many more grains within the disk.

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M. Jura: Department of Astronomy, University of California at Los Angeles, Los Angeles, CA 90024

H. Kroto: School of Chemistry and Molecular Sciences, University of Sussex, Brighton BN1 9QJ, England, UK