THE Massive Disk Around OH 231.8+4.2

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ABSTRACT

We have obtained 11.7 and 17.9 μm images at the Keck I telescope of the circumstellar dust emission from OH 231.8+4.2, an evolved mass-losing red giant with a well-studied bipolar outflow. We detect both a central unresolved point source with a diameter of less than 0.5″ producing $F_o(17.9 \mu m) = 60$ Jy and emission extended more than 1″ away from the star, which is aligned with the bipolar outflow seen on larger scales. We find that the unresolved central source can be explained by an opaque, flared disk with an outer radius of $\sim 5 \times 10^{15}$ cm and an outer temperature of $\sim 130$ K. One possible model to explain this flaring is that the material in the disk is orbiting the central star and not simply undergoing a radial expansion.

Subject headings: circumstellar matter — infrared: stars — stars: AGB and post-AGB — stars: mass loss

1. INTRODUCTION

Solar-type stars typically lose over half their initial main-sequence mass on the asymptotic giant branch (AGB) before becoming white dwarfs (Habing 1996); mass loss is of central importance both in stellar evolution and the replenishment of interstellar matter. While many AGB stars exhibit approximately spherically symmetric mass loss, which can be understood in terms of standard models of the interaction of stellar pulsations and radiation pressure on dust (Lamers & Cassinelli 1999; Willson 2000), others show markedly asymmetric outflows, which are not well understood. Here we report an investigation to learn more about the circumstellar material around OH 231.8+4.2, a star with a distinctive bipolar outflow.

OH 231.8+4.2 appears to be an evolved member of the open cluster M46 (Jura & Morris 1985), and, on the basis of the main-sequence turnoff from this system, this mass-losing star probably had an initial main-sequence mass of about 3 $M_\odot$. Both its cluster membership and “phase-lag” measurements in the reflection nebulosity (Kastner et al. 1992) indicate that the distance to the star is approximately 1.3 kpc. Although the star is buried in an optically opaque circumstellar dust cloud, scattering in bipolar lobes perpendicular to the nominal disk indicates the presence of a luminous M9 star (Cohen & Frogel 1977). The star is variable, with a period that might be as short as 648 days (Feast et al. 1983) or as long as 708 days (Kastner et al. 1992), and its luminosity ranges between $10^4$ and $2 \times 10^4 L_\odot$ (Kastner et al. 1998). The luminosity and effective temperature can be explained if the star lies on the AGB.

At 60 μm, OH 231.8+4.2 is brighter than every other AGB star in the sky except IRC +10216 and the Egg Nebula (RAFGL 2688; see Jura & Kleinmann 1989 and Kleinmann et al. 1978). IRC +10216 is very bright at 60 μm because its distance is only $\sim 150$ pc; it is not uniquely luminous. For OH 231.8+4.2, however, with an estimated distance of 1.3 kpc, as found in the DIRBE data from the COBE satellite, $L_o(60 \mu m)$ can be as large as $3 \times 10^{24}$ ergs s$^{-1}$ Hz$^{-1}$, which is comparable to that from the Egg Nebula and, as shown in Figure 1, is substantially larger than $L_o(60 \mu m)$ displayed by most other mass-losing AGB stars.

The optical and near-infrared morphology of OH 231.8+4.2 indicates that there is a massive disk surrounding the central star (see, e.g., Kastner et al. 1992). Additionally, OH 231.8+4.2 displays a bipolar outflow at radio and optical wavelengths, which is inferred to carry at least 0.3 $M_\odot$ (Reipurth 1987; Morris et al. 1987; Sánchez Contreras et al. 2000; Alcolea et al. 2001). The bipolar morphology exhibits discrete clumps (Alcolea et al. 2001).

Although not directly determined spectroscopically, a plausible assumption to account for the bipolar morphology is that OH 231.8+4.2 is a binary, and thus the outflow may be very flattened (Mastromedos & Morris 1998; Soker & Rappaport 2000; Soker 2002). The nature of the putative companion is unknown. It is unlikely that the companion is a white dwarf since OH 231.8+4.2 does not exhibit any spectroscopic similarity to symbiotic systems.

The dynamic nature of the disk is not known. Is the matter expanding radially outward from the star or is it gravitationally bound and orbiting the star, as appears to be the case for some other evolved red giants with circumstellar envelopes, such as the Red Rectangle (Jura & Kahane 1999)? In order to learn more about OH 231.8+4.2, we have obtained high angular resolution mid-IR images of this system with the Keck I 10 m telescope. Previously, Meixner et al. (1999) have obtained mid-IR images of this system, but with a 4 m telescope. With the larger aperture of the Keck telescope, we can study more compact structures. Many other studies have focused on the large-scale bipolar outflow; here we concentrate on the inner region of the system.

2. OBSERVATIONS

Our data were obtained on 2001 February 5 (UT) at the Keck I telescope, using the Long Wavelength Spectrometer (LWS), which was built by a team led by B. Jones and is described on the Keck Web page. The LWS is a 128 × 128 SiAs BIB array with a pixel scale at the Keck telescope of $0.08$ and a total field of view of $10\″ \times 10\″$. We used the “chop-nod” mode of observing, and two different filters centered at 11.7 and 17.9 μm, with widths of 1.0 and 2.0 μm, respectively. Following Chen & Jura (2001), we used Capella (=HR 1708) for flux and point-spread function cali-
brations. For Capella the FWHM of the image was $0.47$ and $0.49$ at 11.7 \text{ and } 17.9$ \text{$\mu$m}, respectively.

The images in the 11.7 and 17.9 \text{$\mu$m} filters are presented in Figures 2 and 3. The Keck data show an extension at position angle $\sim 22^\circ$ that has a full length of $\geq 3''$. The extended infrared emission that was reported by Meixner et al. (1999) shows the same orientation in the sky as the bipolar lobes detected at other wavelengths. There is also a central unresolved pointlike source. We measure total fluxes of $F_\nu(11.7$ \text{$\mu$m}) = 27 \text{ Jy}$ and $F_\nu(17.9$ \text{$\mu$m}) = 240 \text{ Jy}$. These fluxes are about 50\% greater than the average values determined by the Infrared Astronomical Satellite (IRAS) of $F_\nu(12$ \text{$\mu$m}) = 19 \text{ Jy}$ and $F_\nu(25$ \text{$\mu$m}) = 226 \text{ Jy}$. However, OH 231.8+4.2 is strongly variable at mid-infrared wavelengths. The DIRBE instrument on the COBE satellite measured mean fluxes of $F_\nu(12$ \text{$\mu$m}) = 72 \text{ Jy}$ and $F_\nu(25$ \text{$\mu$m}) = 680 \text{ Jy}$. Thus, our measured fluxes are within the range given by previous observations. If the pulsational period given by Kastner et al. (1992) has remained stable, then our data were obtained near minimum light. Both the COBE and IRAS beams are much larger than the angular resolution that we obtained, but the fluxes reported with these instruments may still be comparable to our results since we detect emission as far as 2\ arcsec from the central source. At this angular offset, we expect the grain temperature to have fallen to 170 K (see below), and thus there would probably be relatively little extended emission beyond this region at 11.7 \text{$\mu$m} and even 17.9 \text{$\mu$m}. We find that the unresolved central sour-

![Fig. 1.](image1.png)

**Fig. 1.**—Histogram of $L_\nu(60$ \text{$\mu$m}) for the “very dusty” AGB stars within $\sim 1$ kpc of the Sun listed by Jura & Kleinmann (1989). The distances are taken from that paper and we used mostly IRAS data for the 60 \text{$\mu$m} fluxes. For both the Egg Nebula and OH 231.8+4.2, we take $L_\nu(60$ \text{$\mu$m}) from the time-averaged COBE data.

![Fig. 2.](image2.png)

**Fig. 2.**—The 11.7 \text{$\mu$m} image of OH 231.8+4.2. North is up and east is to the left. The contour levels (Jy arcsec$^{-2}$) are shown in the color bar.
ces carry about $\frac{1}{4}$ and $\frac{1}{4}$ of the total flux at 11.7 and 17.9 $\mu$m, respectively, so that within the unresolved core $F_{\nu}(11.7 \mu m) = 9$ Jy and $F_{\nu}(17.9 \mu m) = 60$ Jy.

It is notable that OH 231.8+4.2 does display a bright unresolved central source. Other stars with ratios of $F_{\nu}(25 \mu m)/F_{\nu}(12 \mu m) \geq 10$ in the IRAS data, indicative of cold grains, show distinct shells and no central dust source. For example, HD 179821, with $F_{\nu}(25 \mu m)/F_{\nu}(12 \mu m) = 21$, shows a resolved shell with an inner diameter of about $3''5$ (Jura & Werner 1999). In HD 179821, the weak 12 $\mu m$ emission results from few grains being near the star. In the case of OH 238.1+4.2, there are a large number of grains near the star yet the material is relatively cold.

3. THE UNRESOLVED CENTRAL SOURCE

The infrared emission from OH 231.8+4.2 depends in part on the composition and size of the grains. Here we first consider the possibility that the grains are sufficiently small that the emissivity of the particles varies as $\nu^{-1}$ and that the envelope is optically thin. In this case, the average temperature of the grains, $T_{gr}$, can be estimated implicitly from the formula

$$F_{\nu}(11.7 \mu m) / F_{\nu}(17.9 \mu m) = \left( \frac{\nu_2}{\nu_1} \right)^4 \frac{e^{h\nu_1/kT_{gr}} - 1}{e^{h\nu_2/kT_{gr}} - 1} ,$$

where $\nu_2$ and $\nu_1$ correspond to 11.7 and 17.9 $\mu$m, respectively. With $[F_{\nu}(11.7 \mu m)/F_{\nu}(17.9 \mu m)] = 0.15$, then $T_{gr} \approx 120$ K. If the grains act like blackbodies, then $T_{gr} \approx 135$ K is a better fit to the data.

If the material is opaque, then the observed flux, $F_{\nu}$, is given by the expression

$$F_{\nu} = B_{\nu}(T_{gr}) \Omega_{\text{source}} ,$$

where $B_{\nu}$ denotes the Planck function and $\Omega_{\text{source}}$ denotes the solid angle of the source. Since the flux at 17.9 $\mu$m from the innermost $0''5$ is 60 Jy, the minimum blackbody temperature of the grains that emit this radiation is 130 K.

In the simplest of optically thin models (see Sopka et al. 1985), if the grain opacity varies as $\nu^{-p}$, then the temperature of the dust grains, $T_{gr}$, at a distance $D$ from the star can be computed from the expression

$$T_{gr} = T_\ast \left( \frac{R_\ast}{2D} \right)^{2/(4+p)} .$$

Given that OH 231.8+4.2 has spectral type M9, we adopt $T_\ast = 2500$ K (van Belle et al. 1996). With an average value of $L = 1.5 \times 10^4 \ L_\odot$, then $R_\ast = 4.6 \times 10^{13}$ cm. Since the central source is unresolved, we expect that all the emission from the point source arises from a region within $0''25$ of the star, which corresponds to a distance of $4.9 \times 10^{15}$ cm. At this

![Fig. 3.](image-url)
distance, the predicted grain temperature from equation (3) for \( p = 1 \) (a crude averaging of the silicate opacity given by David & Pegourie 1995) is 290 K, much greater than the value inferred from the data. Even if the particles are blackbodies with \( p = 0 \), then the grain temperature is predicted to equal 170 K, which is larger than the inferred value.

A better way to understand the data is to presume a non-spherical circumstellar envelope in which much of the mass is largely confined to a disk. Knapp, Sandell, & Robson (1993) showed that a flat opaque disk cannot explain the spectral energy distribution from OH 231.8+4.2 because in the infrared such a disk should exhibit \( F_\nu \) varying as \( \nu^{-0.33} \), while, in fact, between 12 and 60 \( \mu \)m, the IRAS data indicate that \( F_\nu \) varies as \( \nu^{-2.1} \). Below, we consider a flared disk that when viewed face-on exhibits \( F_\nu \) varying as \( \nu^{-1.67} \) (Chiang & Goldreich 1997). We suggest that emission from a flared disk at a substantial inclination can account for the data.

We can make an estimate of the minimum dust mass in the compact source, \( M_{\text{dust}} \). If it were optically thin, then

\[
M_{\text{dust}} = \frac{F_\nu D^2}{B_\nu(T_\nu)\chi_\nu} ,
\]

where \( D \) denotes the distance to the source. If, as is likely, the system is opaque, then this relationship provides only a lower bound to \( M_{\text{dust}} \). With \( T_\nu = 130 \) K, \( F_\nu(17.9 \mu m) = 60 \) Jy, and \( \chi_\nu = 1000 \text{ cm}^2 \text{ g}^{-1} \) (Ossenkopf, Henning, & Mathis 1992), then \( M_{\text{dust}} \geq 7 \times 10^{28} \) g.

4. A MODEL FOR THE DISK EMISSION

In order to explain the spectral energy distribution of the unresolved source, we present a model to explain the observations of OH 231.8+4.2 that is based on the calculations of Chiang & Goldreich (1997) for passive, opaque disks around pre-main-sequence stars. Although we consider a post-main-sequence system, the basic physical principles can be applied to both sorts of disks. In this model, the heating and cooling rates locally balance each other, and the task is to determine the temperature that achieves this effect. We ignore the illumination of the disk by light from the bipolar lobes.

If the disk has a local temperature, \( T_{\text{disk}} \), then in a flat system that is optically thick in the vertical direction, for \( D \gg R_\ast \),

\[
T_{\text{disk}} \approx \left( \frac{2}{3\pi} \right)^{1/4} \left( \frac{R_\ast}{D} \right)^{3/4} T_\ast .
\]

For a disk in vertical hydrostatic equilibrium that is locally isothermal, the density distribution, \( \rho \), is given by the expression

\[
\rho = \rho_0 \exp \left( - \frac{z^2}{h^2} \right),
\]

where

\[
h = \left( \frac{2D^2 k_B T_{\text{disk}}}{GM_\ast \mu} \right)^{1/2},
\]

and \( \mu \) is the mean molecular weight. In this expression, we ignore the self-gravity of the disk.

The transition from flat to flared disk occurs at a critical distance, \( D_{\text{crit}} \), which is established by the criterion that \( h \geq R_\ast \). From the above,

\[
D_{\text{crit}} = \left( \frac{3\pi}{32} \right)^{1/9} \left( \frac{GM_\ast \mu}{k_B T_\ast R_\ast} \right)^{4/9} R_\ast
\]

and, at this location, the temperature, \( T_{\text{crit}} \), is given by the expression

\[
T_{\text{crit}} = \left( \frac{256}{81\pi^2} \right)^{1/12} \left( \frac{k_B T_\ast R_\ast}{GM_\ast \mu} \right)^{1/3} T_\ast .
\]

Using the stellar parameters for OH 231.8+4.2 described above, assuming that \( M_\ast = 1 M_\odot \) because the star has lost mass during its post-main-sequence evolution, and assuming that the gas is primarily H\(_2\) and He so that \( \mu = 3.9 \times 10^{-4} \) g, then \((2k_B T_\ast R_\ast)/(GM_\ast \mu) = 0.061\). Consequently, \( D_{\text{crit}} \approx 3.0R_\ast \) so that the flaring of the disk begins close to the star. At \( D = D_{\text{crit}} \), the disk temperature, \( T_{\text{crit}} \), is 740 K.

In their models for flared disks, Chiang & Goldreich (1997) define the “grazing angle,” \( \alpha \), as the angle between the surface of the disk and the line of sight to the star. Far from the star,

\[
\alpha \approx D \frac{d}{dD} \left( \frac{h}{D} \right).
\]

In this approximation,

\[
T_{\text{disk}} = \left( \frac{a}{2} \right)^{1/4} \left( \frac{R_\ast}{D} \right)^{1/2} T_\ast .
\]

With these expressions, the disk temperature is given by the expression

\[
T_{\text{disk}} = \left( \frac{1}{7} \right)^{2/7} \left( \frac{R_\ast}{D} \right)^{3/7} \left( \frac{2k_B T_\ast R_\ast}{GM_\ast \mu} \right)^{1/7} T_\ast .
\]

Chiang & Goldreich (1997) discusses models for pre-main-sequence stars whose disks result from the collapse of interstellar clouds. Such disks might have very large amounts of angular momentum and extend to great distances from the star. Here we picture a disk created in a binary system, and the initial angular momentum of the system limits the amount of angular momentum, \( J_0 \), that the disk can possess. Below, we argue that the disk has an angular momentum given by

\[
J = M_{\text{disk}} \sqrt{\frac{GM_\ast D_{\text{out}}}{\pi}},
\]

where \( D_{\text{out}} \) is the outer boundary of the disk that we set equal to \( 3v_{\text{circ}}t \), where these parameters are defined below (see eq. [18]). If OH 231.8+4.2 had, itself, an initial mass of \( 3 M_\odot \) and a companion of \( 1 M_\odot \) in a circular orbit of radius between 3 and 5 AU, then the companion would have had an orbital angular momentum of \(~2 \times 10^{53} \) g cm\(^2\) s\(^{-1}\). If half of this orbital angular momentum has been transferred to the disk so that \( J \sim 10^{53} \) g cm\(^2\) s\(^{-1}\), and if \( M_{\text{disk}} \sim 0.1 M_\odot \), then we find from equation (13) that \( D_{\text{out}} = 6 \times 10^{15} \) cm, consistent with the observational upper limit that \( D_{\text{out}} \leq 5 \times 10^{15} \) cm. According to our models, where \( D_{\text{out}} = 5 \times 10^{15} \) cm, the inferred disk temperature from equation (12) is 130 K and \( h = 3 \times 10^{15} \) cm.
If the disk were nearly face-on, then we would detect emission from essentially every annular ring. However, if the angle between the normal to the disk and the line of sight, $\theta$, is greater than 45°, then the inner, warm portions of the disk are occulted (Chiang & Goldreich 1999). According to Kastner et al. (1992) and Shure et al. (1995), $\theta \approx 54^\circ$, and therefore most of the disk is shadowed from our point of view. As a first approximation, we assume that we only observe emission from the outer portion of the flared disk that has radius, $D_{\text{out}}$, and a uniform temperature, $T_{\text{out}}$. This outer material is so “flared” into our line of sight that its emission dominates the unresolved central source that we detect. If $\Omega_{\text{out}}$ denotes the solid angle subtended by the outer portion of the flared disk from our perspective, then

$$\Omega_{\text{out}} \approx 4 \left( \frac{D_{\text{out}}}{D_*} \right)^2 \sin \theta . \quad (14)$$

We can use equation (2) to estimate the flux from the source.

The comparison of the model with the data is shown in Figure 4, where we present the results for both $D_{\text{out}} = 5 \times 10^{15}$ cm (and $T_{\text{out}} = 130$) and an alternative model with $D_{\text{out}} = 5 \times 10^{15}$ cm (and $T_{\text{out}} = 160$ K). The model with $D_{\text{out}} = 5 \times 10^{15}$ cm agrees with our observations of the compact emission at 11.7 and 17.9 $\mu$m to better than a factor of 2. Our model does not reproduce the total flux from the system since our observations show that the bipolar lobes contribute the majority of the flux from OH 231.8+4.2 at 17.9 and 11.7 $\mu$m. The results from the model suggest that much of the millimeter and submillimeter continuum are produced by the compact source. This is possible but unproven. We do not know the millimeter-wavelength opacity of the particles around OH 231.8+4.2, and the disk may not be fully opaque at these wavelengths from the perspective of the Earth. In fact, the model significantly overestimates the flux at the longest observed wavelength of about 3 mm. The apparent agreement between the model and many of the integrated millimeter and submillimeter fluxes shown in Figure 4 may be a coincidence. Also, at 4.9 $\mu$m, the observed DIRBE flux is 16 Jy, which agrees with ground-based measurements (Woodward et al. 1989) and, furthermore, this is the total flux expected from the photosphere. The map of Woodward et al. (1989) shows that the emission at 4.7 $\mu$m is extended and much of it is probably scattered radiation. The amount of disk thermal emission at wavelengths shortward of 11.7 $\mu$m is not easily measured and is, therefore, not included in Figure 4.

5. DISK DYNAMICS

The model proposed here is geometrically similar to that proposed by Cohen et al. (1985). What is uncertain is whether the disk material is expanding radially or whether it is orbiting; the expansion rate is not well measured. It has usually been assumed that the disk is expanding radially at the characteristic outflow speed of 20 km s$^{-1}$. At this speed, the material reaches the inferred value of $D_{\text{out}}$ of $5 \times 10^{15}$ cm in approximately 80 yr. If, however, the disk is in vertical hydrostatic equilibrium, then the vertical sound crossing time must be short compared to the expansion time. In the outermost region, the disk temperature may be ~100 K and therefore possess a sound speed near 1 km s$^{-1}$. Since the vertical displacement approaches $5 \times 10^{15}$ cm, the time to achieve vertical hydrostatic equilibrium and, thus, the implied disk lifetime is at least ~2 $\times$ 10$^3$ yr. It is easier to understand the presence of a flared disk if the material is orbiting.

Pringle (1991) has presented a model of how viscous disks around binary stars may expand as angular momentum is transferred from the binary stars into the disk, and here we follow his model. In the standard treatment of accretion disks, matter flows inward while angular momentum flows outward. Pringle (1991) argues that for a circumbinary disk, the binary system can provide enough torque to the disk so that no matter flows inward, but the outward flow of angular momentum still occurs. In this model, after the disk is formed, its mass remains constant. The torque operates as the binary creates a tide in the circumbinary disk (Lin & Papaloizou 1979).

We assume that the circumstellar matter is injected into the system as a narrow ring of mass, $M_{\text{disk}}$, and an inner radius, $D_{\text{in}}$. The ring then expands as angular momentum is transferred from inner to outer regions by viscosity, $\nu$, which can be written as

$$\nu = \frac{2\alpha \gamma_s c_s^2}{3\Omega} . \quad (15)$$

Here, $\alpha$ is the usual dimensionless parameter and is taken to be $\leq 1$, $c_s$ is the speed of sound or $(\gamma k_B T_{\text{disk}}/\mu)^{1/2}$, where $\gamma$ is the ratio of specific heats, and $\Omega$ is the local angular velocity of the disk, $(GM_*/D^3)^{1/2}$.
Following Pringle (1991), we make the approximation that the gas temperature falls as $D^{-1/2}$ so that

$$T_{\text{disk}} = T_{\text{in}} \left( \frac{D_{\text{in}}}{D} \right)^{1/2},$$

where $T_{\text{in}}$ is the temperature at the inner boundary of the disk, $D_{\text{in}}$. This radial variation of the temperature is somewhat different from that described in equation (12), but it should not lead to any essential change in the physics of the outflow. It does allow for a simple analytic solution to the asymptotic disk evolution. Following Pringle, with this radial variation of the temperature, we define $v_{\text{vis}}$ (denoted $k$ by Pringle) as a characteristic speed of the outflow induced by the viscosity, such that $v_{\text{vis}} = \nu / \alpha$, and is given by the expression

$$v_{\text{vis}} = \frac{2\gamma k B T_{\alpha}}{3\mu} \left( \frac{D}{GM_{*}} \right)^{1/2}.$$  

Because $T$ scales as $D^{-1/2}$, $v_{\text{vis}}$ is independent of $D$.

The inner radius of the disk might be $\sim 1.7$ times greater than the orbital separation of the binary pair (Artymowicz & Lubow 1994). Although uncertain, we adopt $D_{\text{in}} = 3R_{*} = 1.3 \times 10^{14}$ cm where $T_{\text{disk}} = 740$ K (see above). The value of $\alpha$ is not well known for the material around OH 231.8+4.2. Saslaw (1978) has shown that grains around a variable star move in noncircular orbits, and these noncircular motions might produce a substantial viscosity. We assume that $\alpha = 1$, implying that $v_{\text{vis}} = 0.29$ km s$^{-1}$.

After the initial conditions damp out, Pringle’s model for the outer portion of the disk has a surface density given by the expression

$$\Sigma \approx \frac{M_{\text{disk}}}{12\pi^{3}D_{\text{vis}}^{2}t^{1/2}} \exp \left( -\frac{D}{3v_{\text{vis}}t} \right),$$

where $M_{\text{disk}}$ is the mass of the disk. This expression for the surface density of the disk appears to be independent of the torque being exerted on the disk because the transfer of angular momentum from the binary to the disk is effected by employing the inner boundary condition of the solution for the disk evolution that no matter flows inward even though matter and angular momentum flow outward. That is, at all times, the mass of the disk is constant and

$$\int_{0}^{\infty} 2\pi D \Sigma(D) dD = M_{\text{disk}}.$$  

The disk angular momentum, $J$, is given by

$$J(t) = M_{\text{disk}} \sqrt{\frac{3GM_{*}v_{\text{vis}}t}{\pi}}.$$  

From equation (18), we write that $D_{\text{out}} \approx 3v_{\text{vis}}t$.

According to Pringle (1991), the characteristic time for the torque to operate on the disk, $t_{\text{torque}}$ at the innermost radius is given by the expression

$$t_{\text{torque}} = \frac{4D_{\text{in}}^{2}}{3v_{\text{vis}}} = \frac{2\mu \sqrt{GM_{*}D_{\text{in}}}}{\alpha k B T_{\text{in}}^{3/2}}.$$  

Thus, for the disk around OH 231.8+4.2, this characteristic time for the torque to operate is $\sim 200$ yr. The outflow time is $D_{\text{out}} / v_{\text{vis}}$ or about 5000 yr. Therefore, the time for the torque to be effective is considerably less than the inferred outflow time. Alcolea et al. (2001) derive a minimum age of the bipolar outflow from OH 231.8+4.2 of 770 yr. Thus, the time noted here for the flared disk to expand to its current estimated size is comparable to the minimum lifetime of the system.

6. DISCUSSION

We have suggested that the circumstellar disk around OH 231.8+4.2 is gravitationally bound and orbiting the system rather than simply undergoing a radial expansion. Underlying this picture is that OH 231.8+4.2 is an AGB star with a hitherto unseen companion. Ignace, Cassinelli, & Bjorkman (1996) have suggested that mass loss from a red giant with a sufficiently large rate of rotation—perhaps induced by a companion (Livio & Soker 1988)—could produce disk material within a few stellar radii of the mass-losing star. Whether this disk is bound or unbound—that is, whether it is orbiting or expanding—is not easily calculated because the acceleration law of the material near the star is not known. In fact, the acceleration may be time-variable over several pulsational cycles (Winters et al. 2000). Although it is possible that an orbiting ring could be formed near a rotating AGB star, this is unproven. Once such a ring is formed, as discussed above, Pringle (1991) has proposed that the material could expand by the viscous dissipation of angular momentum contained within the orbiting central binary.

Although there are a large number of studies of the molecular gas around OH 231.8+4.2, there is no direct kinematic demonstration from observations of the circumstellar gas that the disk around OH 231.8+4.2 is orbiting. Most of the gas emission is dominated by material in the bipolar flow that subtends a solid angle of $\sim 10^{-4}$ sr. The flared disk probably only subtends a solid angle of $\sim 10^{-11}$ sr. Therefore, the disk emission is mostly overwhelmed by the extended emission from the bipolar flow and, in order to detect the disk, interferometry is required.

One molecule that has been extensively studied at high angular resolution is OH. A remarkable aspect of OH 231.8+4.2 is that the centroid of the OH maser emission is offset by $1''$ to the southwest from the SiO and H$_{2}$O masers and the millimeter continuum (Gomez & Rodriguez 2001; Zijlstra et al. 2001; Sánchez Contreras et al. 1998). One possible explanation of this is that since OH is produced from the photodissociation of H$_{2}$O (Glassgold 1996), a one-sided ultraviolet flux might produce a one-sided concentration of OH, which might explain the CO profile toward HD 188037 (Jura et al. 1997). Since M46 with its concentration of ultraviolet-emitting A-type stars also lies to the southwest of OH 231.8+4.6, we suggest that the displacement of the OH masers from the core of OH 231.8+4.6 may be a consequence of its position in the outer, northeast portion of M46.

Alcolea et al. (2001) report interferometric maps of the CO emission with resolution as high as $1''5 \times 0''.7$. They distinguish between the extended bipolar flow and a central core. Even the central core displays both the north-south outflow plus a central equatorial disk or torus. The innermost disk or torus is not well mapped in their data, and it is not possible to determine whether it is orbiting or expanding.

Sánchez Contreras et al. (2000) report interferometric observations of HCO$^+$, SO, H$^{13}$CN, and SiO around OH
231.8+4.2. The SO is particularly sensitive to high density regions, but the angular resolution of the maps, $4.2\times 2.2$, is insufficient to distinguish an orbiting disk of radius $5 \times 10^{15}$ cm. Sánchez Contreras et al. (2000) report an expanding disk or ring of radius $2 \times 10^{16}$ cm at speed of $6$–$7$ km s$^{-1}$. The relationship between this observed large disk of $2 \times 10^{16}$ cm radius and the orbiting disk of $5 \times 10^{15}$ cm radius that we propose to exist is unclear. Interferometric observations of the circumstellar H$_2$O masers report two velocity peaks separated by $3.1$ in the north-south direction (Gomez & Rodriguez 2001). This orientation suggests that this emission may be excited in the bipolar flow rather than the disk.

On a scale of $0.005$, Sánchez Contreras et al. (2002) report SiO maser emission that is in the east-west direction and with kinematics that are consistent with being infalling material at a speed of $\sim 10$ km s$^{-1}$, with some additional rotation at a speed, $V_{rot}$, of $\sim 6$ km s$^{-1}$. The inferred rotation is measured over a spatial scale of approximately the diameter of the star. Unless the system is nearly face-on, the apparent rotation is too small to be orbital motion; it must reflect rotation of the star. The total angular momentum of an AGB star is about $\frac{1}{2} M_\star R_* V_{rot}$ (Soker 1998); OH 231.8+4.2 may currently possess $\sim 10^{52}$ g cm$^{-2}$ s$^{-1}$ of angular momentum. Above, we suggest that the disk may possess $\sim 10^{52}$ g cm$^{-2}$ s$^{-1}$ of angular momentum. Thus, it is imaginable that there might be enough angular momentum in the system to account for the proposed disk. We conclude that the available interferometric data are consistent with the hypothesis of an orbiting disk with an outer radius of $5 \times 10^{14}$ cm, but they do not lend any support to the model. The argument for the existence of an orbiting rather than expanding disk is indirect. While the predicted infrared emission from a flared, orbiting disk agrees with our data, we cannot rule out other models for the compact, mid-infrared emission.

The mass of the disk around OH 231.8+4.2 is uncertain. Above we derived a minimum mass of dust of $10^{29}$ g that would correspond to a total of about $0.01 M_\odot$ if the gas-to-dust ratio is $\sim 160$. The maximum possible dust mass is about $1.0 M_\odot$, since this would require that most of the material lost by OH 231.8+4.2 was trapped in the disk. However, a disk of this mass could not be both orbiting and as large as $5 \times 10^{15}$ cm because it would possess too much angular momentum. It is possible that the disk around OH 231.8+4.2 has about $0.1 M_\odot$. In this case, the disk mass around OH 231.8+4.2 is larger than that for disks around other evolved red giants except, perhaps, the Red Rectangle (see Jura & Kahane 1999). With time, the circumbinary disk around OH 231.8+4.2 must evolve. If, in fact, the material is orbiting, then macroscopic solids and even planets might eventually form.

7. CONCLUSIONS

We have obtained 11.7 and 17.9 $\mu$m images of OH 231.8+4.2; we identify an unresolved central source with $F_{\nu}(17.9 \mu$m) = 60 Jy. We propose that this emission results from a flared disk with an outer temperature of 130 K and an outer disk radius of $5 \times 10^{15}$ cm. One possible model that is consistent with the data is that this flared disk is orbiting rather than simply expanding.

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