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OBSERVATION OF A BURST OF HIGH-VELOCITY DUST FROM α HERCULIS

K. Tatebe, D. D. S. Hale, E. H. Wishnow, and C. H. Townes
Space Sciences Laboratory and Department of Physics University of California, Berkeley, CA 94720;
tatebe@ssl.berkeley.edu, david@isi.mtwilson.edu, wishnow@ssl.berkeley.edu, cht@ssl.berkeley.edu
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ABSTRACT

Interferometric observations of α Herculis at a wavelength of 11.15 μm over the period 1989–2004 show large visibility variations. These variations are interpreted as an ejection of approximately $10^{-6}\ M_\odot$ of material in 1990 that has subsequently expanded and dissipated. The expansion rate is approximately 75 km s^{-1}, much larger than previous observations. No substantial material has been emitted during the subsequent 14 years.

Subject headings: infrared: stars — stars: individual (α Herculis) — stars: late-type — stars: winds, outflows — techniques: interferometric

1. INTRODUCTION

The irregular variable M star α Herculis has had episodic changes in intensity and has emitted material at estimated rates of 10^{-7} to $10^{-9}\ M_\odot$ yr^{-1}. The distribution of the resulting dust around the star in 1993 was inferred by the visibility measurements of Danchi et al. (1994) using the Infrared Spatial Interferometer (ISI) of the University of California at Berkeley. A long series of measurements with the same instrument now show that the dust shell moved away from the star quite rapidly, with velocities of about 75 km s^{-1}, and that for somewhat more than the subsequent decade, very little material has been emitted by the star. This speed is surprisingly fast compared with typical measured outflow rates. Velocity components of 13 and 25 km s^{-1} in the outflow of α Her have been reported by Bernat (1981).

2. PAST MEASUREMENTS AND INTERPRETATIONS OF STELLAR VISIBILITIES

A record of the 11.15 μm visibility of α Her from 1979 to 2004 as measured by the ISI is given in Table 1. The record includes measurements over a range of spatial frequencies from 2 to 9 spatial frequency units (SFU) as the telescope baseline was varied; an SFU is defined as 10^5 cycles rad^{-1}. Over the measurement period, the visibility of α Her at higher spatial frequencies shows large variations, and these are interpreted in this Letter as a large mass ejection event followed by the dissipation of this material. The letters in Table 1 identify the high SFU measurements under discussion.

Figure 1 illustrates ISI measurements obtained from 1979 to 1992 (Danchi et al. 1994). The visibility values near 0.5 over the range 6–12 SFU were obtained in 1992 (point B in Table 1), and they indicate that a substantial dust envelope surrounding the star has been resolved. Broadly speaking, visibilities in the range 6–9 SFU represent the brightness ratio of the star relative to the star and dust combined. At spatial frequencies greater than ~8 SFU, the dust should be almost fully resolved, and only the star should be small enough to create a fringe. Once the dust is resolved, the visibility does not vary much until spatial frequencies are high enough to resolve the star itself.

Figure 1 also includes visibilities prior to 1992. The open circle near 4 SFU is from 1979, and the filled circles near 3 SFU are from 1989. These low-frequency measurements are striking in that they do not agree with the modeled visibility given by the solid curve. This discrepancy was not explained in Danchi et al. (1994), but it presumably arises because there was little dust in 1989 and much more in 1992. The theoretical curve is due to a model consisting of a spherical shell of dust surrounding the star. The shell has a temperature of 518 K, an inner radius of 250 mas, and it extends to an outer radius of 350 mas. The low-frequency points are consistent with a much smaller object, as would be the case if the dust had not yet been produced or was closer than 100 mas from the center of the star. Hence, this figure alone indicates that emission of material and dust formation occurred between 1989 and 1992.

Visibility measurements of α Her have been conducted at the ISI during the period 1993–1999. Average visibilities over the range 6–9 SFU are plotted as a function of time in Figure 2. The letters in this figure correspond to the letters in Table 1. Following the low visibility of 0.5, i.e., Figure 1 (point B), the visibility rises rapidly to 0.7 (point C), indicating that the star is contributing progressively more of the total flux of the object. The points D and E are near unity, indicating that since 1998 very little dust has been present. The visibility is also near unity for measurements in 2003 and 2004, labeled F and G in Table 1, respectively.

Visibility measurements at higher spatial resolutions (20–40 SFU) were made in 2000 and 2001. These data have been analyzed by fitting the visibility with a uniform disk model in order to determine the stellar diameter (Weiner et al. 2003). These fits indicate that about 5% of the flux of the object is from the resolved dust, and this is again consistent with the measurements of 1998–2004.

Figure 2 provides the basis for a picture in which α Her emits material in approximately 1990, the dust shell expands until it emits radiation comparable to the star in 1992, and then the dust continues to expand and dissipate. It is interesting to compare these visibility changes to photometric variations of α Her. Also plotted in Figure 2 is a 60 day running average of visible photometry from AAVSO (*solid line*) and *Hipparcos* *V*-band photometry (*gray circles*). The minimum of the *Hipparcos* photometry suggests that the minimum visibility may have actually occurred 100 days earlier than the lowest one measured. Photometric data at 12 μm from the DIRBE on the *COBE* satellite are available during 1990, a period near point A, and show a relatively constant flux of 1121 Jy with a standard deviation of 54 Jy.

No striking correlation is apparent in Figure 2 between the AAVSO data and the ISI visibility measurements. The *Hipparcos* data, however, show a decline in the star's brightness that is well correlated with the appearance of the dust. The

TABLE 1
ISI VISIBILITIES OF α HER

Average Date	Average SFU	Average Visibility	Probable Error	Point
1979	4.3	0.95	0.07	
1989 Oct	2.9	1.03	0.05	
1990 Jul	9.0	0.68	0.07	A
1992 Aug	8.8	0.50	0.05	B
1993 Sep	6.5	0.71	0.03	C
1996 Aug	2.2	0.99	0.07	
1998 Sep	7.0	0.95	0.03	D
1999 Sep	9.1	0.91	0.02	E
	3.0	0.99	0.01	
2003 Oct	2.1	0.97	0.03	
	4.1	1.01	0.03	
	6.2	0.93	0.05	F
2004 Sep	2.5	1.00	0.01	
	5.0	0.92	0.01	
	7.5	0.91	0.01	G

NOTE.—A summary of 11.15 μm visibilities. The 1979, 1989, and 1992 values were previously published (Danchi et al. 1994). Average visibilities refer to an average over a range of spatial frequencies. The labels denote observations referred to in the text and Fig. 2.

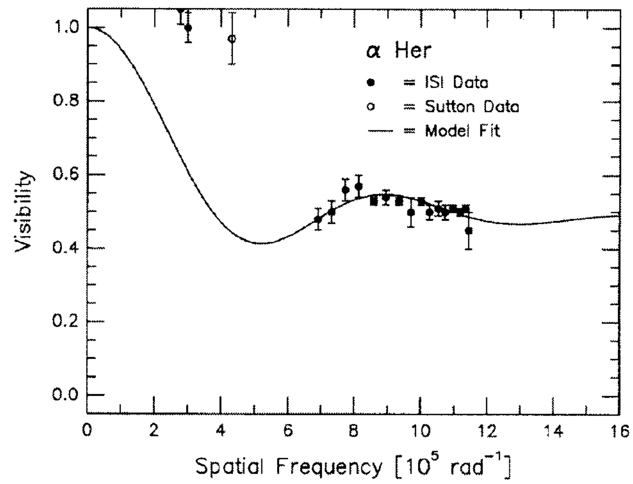

FIG. 1.—ISI visibilities as a function of spatial frequency units (SFU). The open circle near 4 SFU represents a measurement made in 1979, and the two filled circles near 3 SFU are from 1989. The filled circles in the range 7–12 SFU (B in Table 1) were measured in 1992. The solid curve represents the theoretical visibilities from the model of Danchi et al. (1994).

minimum brightness coincides with minimum visibility, and the star becomes somewhat brighter again as the visibility climbs. Unfortunately, there are no later *Hipparcos* data to help establish a firm correlation between the photometry and the rising visibility points as the dust disappears. The AAVSO luminosity data are in good agreement with data by Wasatonic (1997), and both show variations of 80 Jy or more on timescales of 124 days (Kiss et al. 2006) when regarded without a running average. The rapid variations of the *Hipparcos* luminosity curve are surprising, with the luminosity changing by as much as 50 Jy in as little as 30 days.

The temporal visibility changes described above imply high outflow velocities of the dust. In Figure 1, the 1989 points imply a dust shell radius of at most ∼100 mas, and by 1992 the dust shell radius is modeled as ∼300 mas. The apparent angular expansion rate is therefore 200 mas in 2.8 yr, or at least 71 mas yr^{-1}, and possibly faster.

The change in visibility between points A and B of Figure 2 gives similar evidence of the rapid motion of the dust. The dust is assumed to have been fully resolved in 1992 (point B), when the visibility was 0.5, and at all later times. Before this time, i.e., point A in 1990, the visibility was higher, yet the dust shell must have been smaller. This indicates that the interpretation of the visibility as the ratio of stellar to total luminosity must break down at this earlier time. That is, the dust shell was not yet large enough to be fully resolved. The measured visibility of 0.68 at 9 SFU in 1990 is consistent with a dust shell size of no more than about one-third that of the shell modeled in Figure 1 for the 1992 data, or about 100 mas. This is approximately the minimum distance from the star where dust could first condense. These figures indicate an increase of about 100 mas yr^{-1} from 1990 to 1992.

3. MODELS OF DUST TEMPERATURE AND FURTHER ESTIMATES OF EXPANSION RATES

The dust shell expansion can be examined in more detail using a model of the star and warm dust shell. The stellar diameter has been measured at a wavelength of 2.2 μm to be 33.15 ± 0.75 mas (Perrin et al. 2004). The diameter measured at 11.15 μm wavelength is 39.32 ± 1.04 mas (Weiner et al. 2003). The star's temperature is estimated, from the *K*-band size of 33.15 mas, to be 3285 K (Perrin et al. 2004). For modeling, we assume the 11.15 μm diameter of 39.32 mas and a temperature of 3000 K, which provides approximately the same luminosity as the model of Perrin et al. (2004). The distance to α Her is assumed to be 117^{+57}_{-29} pc from *Hipparcos* parallax measurements of 8.53 ± 2.8 mas (Perryman et al. 1997). Radiation from dust surrounding the star depends on its temperature, determined primarily by absorption of stellar radiation. Two extreme models for the dust's warming are used: (1) the dust particles are completely black, in which case their temperature decreases with increasing distance from the star proportional to $(R_S/R_D)^{1/2}$, where R_S is the stellar radius and R_D is the dust shell radius; and (2) the dust particles act only as scatterers over a very narrow band of radiation, in which case their radiation decreases as $(R_S/R_D)^2$. This is an extreme assumption and is unlikely to be accurate, but it will be used to examine the range of possibilities. We approximate the dust as a simple shell at a distance 300 mas from the center of the star in 1992,

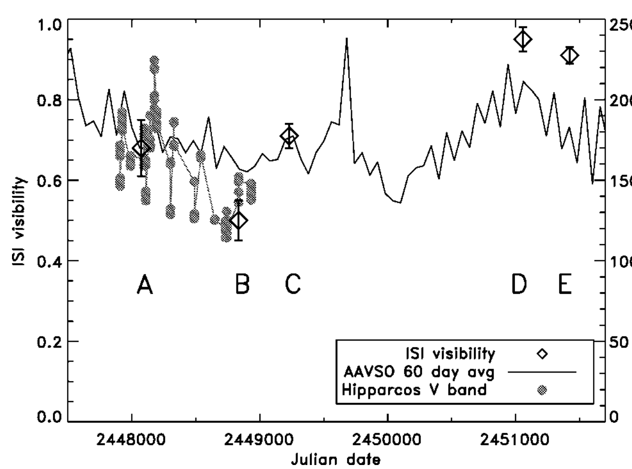

FIG. 2.—ISI visibility as a function of time. Each diamond is an average of visibilities in the range 6–12 SFU. The rapid rise from B to C is interpreted as an expansion of a dust shell. A 60 day running average of the AAVSO photometry is plotted as a line, and the *Hipparcos* photometry data are plotted as connected gray circles. Both photometry curves are in units of janskys, as indicated by the right axis.

which is the average of the range of values 250–350 mas given by Danchi et al. (1994).

If the dust particles were black, case 1, and the shell were optically thin, then their temperature would be

$$T_D = T_S \left(\frac{R_S}{2R_D}\right)^{1/2}, \quad (1)$$

where T_D and R_D are the temperature and radius of the dust shell, respectively, while T_S and R_S are those of the star. The factor of 2 is a consequence of each dust grain in the optically thin shell radiating into a solid angle of 4π, while each point on the stellar surface radiates into only 2π.

For the shell at 300 mas, this gives the dust a temperature of 543 K, close to the value of 518 K assumed by Danchi et al. (1994). In 1992 when the dust was resolved but not the star, as seen in Figure 2 (point B), the visibility (i.e., the ratio of stellar to total luminosity) was close to 0.5. This indicates that the dust gave the same amount of flux as the star, assuming that the shell were quite transparent. If the dust radiates as a blackbody, then the ratio of power emitted by the dust relative to the star at 11.15 μm should scale as

$$\frac{P_*}{P_D} = \frac{1}{4}\frac{R_*^2[(\exp(1290/T_D) - 1]}{R_D^2[(\exp(1290/T_*) - 1]}\frac{(1-\epsilon)}{\epsilon}, \quad (2)$$

where ϵ is the dust opacity. The factor of 4 results from the dust shell being optically thin, allowing all 4π of the shell to be seen in contrast to the star, where only a uniform disk is seen.

For $T_D = 543$ K and $R_D = 300$ mas, the opacity can be shown to be 0.02. So, indeed, only a small fraction of the 11.15 μm radiation from the star was absorbed, and fluxes from the dust and the star were very close to equal in 1992. In 1993, a year later, the visibility was 0.71 (see Table 1, point C), so the ratio of dust-to-star radiation was then 0.41.

Allowing for a modest decrease in the telescopes' reception of radiation with increasing angular size due to the telescopes' finite beam width, this model implies that the temperature is reduced to 435 K. The distance from the star would then have increased by a factor $(543/435)^2$ or to 467 mas. The expansion rate would therefore be 167 mas yr^{-1}.

In the extreme situation, in which the dust radiation intensity decreases proportionately to $(1/R_D)^2$, case 2, the shell would have expanded by a factor of $(1/0.41)^{1/2}$ or to 469 mas, and the expansion rate would be 169 mas yr^{-1}, close to the same value.

By 1998, the visibility at 7 SFU increased to $0.95 \pm .03$ (point D). At this resolution, the size of the star itself would only be resolved enough to decrease the visibility by approximately 0.02, so the dust would not be contributing a flux of more than about 6% that of the star. For dust of blackbody characteristics, this implies a temperature as low as 320 K and a distance as large as 864 mas, allowing for the fractional transmission of light from this radius of only 0.34 due to the beam of the telescopes. The expansion rate between 1992 and 1998 for case 1 would then be 94 mas yr^{-1}.

Of course, the particles may not be completely black, which would change the above results somewhat. If we again make the extreme assumption that the particles simply scatter light over a narrow bandwidth, case 2, the relative intensity should decrease proportionally to the inverse square of the distance. From the 1998 results, this would imply a distance of 790 mas, giving an expansion rate of 82 mas yr^{-1}. A reasonable compromise between the two values would perhaps be 90 mas yr^{-1}. Because the radiation contribution from the dust shell is so small, this does not represent a very precise figure but rather a lower limit to the rate of expansion.

4. DISCUSSION

It is sensible to search for alternative models, such as the influence of companion stars, that would account for such rapid variations in the visibilities. The well-known companion star of α Her, a G star, is separated from it by about 5″ (Deutsch 1956). Thus, it should have little effect on the dust shell surrounding α Her within a distance of less than about 1″. Other closer companions are suggested by McAlister et al. (1989). Closer companions might be used as a surprising means to capture the gas and dust through accretion without producing easily detectable effects. Although a companion might provide a mechanism to rapidly remove the dust, it would still be unable to explain the rapid appearance of dust. High speeds are still required for the dust to appear at a distance of about 300 mas after it was clearly at much smaller distances in 1989 and 1990. Another possible mechanism might be to remove the dust through evaporation caused by heating due to intense turbulence in the high-speed flow; however, if such heating were present, it would be difficult to explain why the dust condenses in the first place. Thus, dust outflow remains the most compelling explanation for the rapidly changing visibilities.

The relative orientation of the star to the baselines varied by 1° for the 1992 data and 4° for the 1993 data. The average orientation differed by 10° between the two years. Since the dust emission is likely to be very roughly symmetric, such small variations are probably not of substantial importance to the results discussed. Even nonspherical distributions would still need high-velocity dust for the projected speed of the dust along the measured baselines to equal the quoted value. This would make the velocities measured here a lower bound on the maximum velocity of the dust along its primary direction of motion.

Acceleration by radiation pressure seems inadequate to produce such high velocities in the dust. The steady state velocity of dust due to radiation pressure has been shown to be proportional to $L^{0.3}$, where L is the luminosity of the star (Habing et al. 1994). The weak dependence of the outflow velocity on the luminosity requires an unrealistically high luminosity to generate the velocities reported here. Measurements of α Her by Danchi et al. (1994) and Benson et al. (1991) indicate a luminosity typical of variable stars and is consistent with a normal outflow velocity of about 30 km s^{-1}. Increasing the dust-to-gas ratio by a factor of 9 could produce velocities as high as 75 km s^{-1} in the model described by Habing et al. (1994); however, this seems unlikely, and an alternate mechanism for accelerating the dust is likely needed.

Table 1 shows that visibilities at spatial frequencies as low as about 3 SFU have always been measured to be near unity. For spatial frequencies in the range 6–9 SFU, the dust was resolved in the early 1990s, giving lower visibilities, but from 1998 to 2004, even at the higher resolutions, the visibility has been close to unity, about 0.95. Thus, the dust should not be contributing more than about 5% of the 11.15 μm radiation, except for possibly some unresolved dust very near the star. Even dust quite close to the star in the later years seems unlikely because of high-resolution measurements made in 2001 (Weiner et al. 2003). Phase closure measurements, which can indicate asymmetry in the distribution of radiation, have been recently made using the three 1.65 m telescopes of the ISI

(Tatebe et al. 2006). The phase closure for α Her, using east-west baselines of 4, 8, and 12 m, was measured to be $0.13° \pm 0.31°$ in 2003 and $0.03° \pm 0.33°$ in 2004. This indicates an almost perfect symmetry in the east-west direction. While this does not completely disprove the existence of dust, it is consistent with little contribution to the radiation from dust, since the dust surrounding the stars has frequently been found to be somewhat asymmetric.

The total mass of the dust shell observed in 1992 is modeled as $10^{-6}\ M_{\odot}$ (Danchi et al. 1994). Assuming a distance of 117 pc, if the shell is moving at 72 km s^{-1}, then it requires about 1 year to move the 100 mas distance between the inner and outer shell radii. This may have been the duration of the emission of the material. This is only an upper limit to this duration, however, because material is likely to have been ejected at various velocities, perhaps spreading over a range as large as 20–30 km s^{-1}, which could produce much of the spread in angular distribution. For the following 14 years, there has been no evidence of substantial further emission.

5. CONCLUSIONS

To summarize the estimates of expansion rates, we note that between 1989 and 1992, the rate was greater than 71 mas yr^{-1}. Between 1990 and 1992, a rate of about 100 mas yr^{-1} is inferred. From 1992 to 1993, the expansion rate calculated is 167 mas yr^{-1}. From 1992 to 1997, the estimated rate is again somewhat more than 100 mas yr^{-1}, which is not very accurate but more or less a lower limit. Hence, we conclude that with the rates of expansion given by these various estimates, with the value of 167 mas yr^{-1} perhaps the most accurate, the expansion rate must be as large as about 130 mas yr^{-1}. This corresponds to a velocity of 72 km s^{-1} for the distance of 117 pc. Such a velocity is surprisingly high and is much larger than velocities measured by Doppler shifts for gas around α Her during other years. This high velocity, however, seems inescapable unless the dust forms and disappears by some unknown mechanism rather than expanding away from the star; α Herculis thus appears to have thrown off a burst of material, of mass about $10^{-6}\ M_{\odot}$, near 1990, and the resulting dust moved rapidly enough to indicate velocities of the material at least as high as 72 km s^{-1}. Since that time, very little additional material has been emitted. Obviously, if such an outburst occurs again, careful observations of the star using many different techniques would help provide details about such an event.

The data from *Hipparcos* was obtained from the SIMBAD database, the visual photometry from R. D. Wasatonic, and the 12 μm photometry from the LAMBDA-DIRBE database. We also acknowledge use of the AAVSO International Database and thank the international observers for their contributions to it. We gratefully acknowledge support from the Office of Naval Research, the National Science Foundation, and the Gordon and Betty Moore Foundation.

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