ISOCAM MOLECULAR HYDROGEN IMAGES OF THE CEPHEUS E OUTFLOW
ALBERTO NORIEGA-CRESPO
Infrared Processing and Analysis Center, Mail Stop 100-22, California Institute of Technology, Pasadena, CA 91125; alberto@ipac.caltech.edu

PETER M. GARNAVICH
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; peterg@cfa.newton.harvard.edu

AND

SERGIO MOLINARI
Infrared Processing and Analysis Center, Mail Stop 100-22, Jet Propulsion Laboratory, Pasadena, CA 91125; molinari@ipac.caltech.edu

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ABSTRACT

The physical characteristics of the Cepheus E “embedded” outflow are analyzed using ISOCAM images in the v = 0–0 S(5) 6.91 μm and S(3) 9.66 μm molecular hydrogen lines. We find that the morphology of the Cep E outflow in the ground vibrational H₂ lines is similar to that in the near-infrared v = 1–0 2.12 μm line. At these mid-infrared wavelengths, we detect neither the second H₂ outflow that is almost perpendicular to the Cep E 2.12 μm flow nor traces of H₂ emission along the second ¹²CO J = 2–1 outflow, at an angle of ~52°, down to a surface brightness of 12–46 μJy arcsec⁻². We do detect at 6.91 μm the likely source of the main H₂ and CO outflows, IRAS 23011+6126, and show that the source is easily seen in all IRAS bands using HIRES images. The source is not detected at 9.66 μm, but we think this agrees with the interstellar extinction curve, which has a minimum at ~7 μm but rises at ~9.7 μm as a result of the strong absorption silicate feature, enhanced in this case by a cocoon surrounding the Class 0 object. This idea is supported by our models of the spectral energy distribution (SED) of the central object. The models assume that the main source of opacity is due to bare silicates, and our best fit for the SED yields a total envelope mass of 17 M☉ and a dust temperature of 18 K.  

Key words: infrared radiation — ISM: jets and outflows — stars: formation — stars: pre-main-sequence

1. INTRODUCTION

The Cepheus E outflow is an excellent object to study the relationship between the physical properties of optical stellar jets and embedded outflows. The existence of a molecular CO flow originating in the region was first indicated by Fukui (1989) in his catalog of molecular outflows, but it was the K′ image of Hodapp (1994), from his imaging survey of molecular outflows, that brought Cep E to the forefront. The south lobe of Cep E is observed optically in Hα and [S ii] λλ6717, 6731 (Noriega-Crespo 1997), and it has been named Herbig-Haro (HH) object 337 (Devine, Reipurth, & Bally 1997). The spectrum of this lobe displays one of the lowest ionizations measured in HH objects, with a ratio [S ii]/Hα = 8.8B ± 0.2 (Ayala et al. 1998). 

Cep E is bright in H₂ emission lines at 2 μm and is likely driven by the source IRAS 23011+6126, presumably a Class 0 object (Eislöffel et al. 1996). Because of its complex morphology and strong H₂ emission, Cep E has been used to gauge the reliability of three-dimensional molecular jet models (Suttner et al. 1997). There is also clear evidence of a second outflow in H₂ almost perpendicular to the main flow emission, as indicated by some faint H₂ knots (Eislöffel et al. 1996). Perhaps more surprising is the presence of a second molecular CO outflow, detected in both the ¹²CO J = 2–1 and J = 1–0 molecular lines (Ladd & Hodapp 1997; Ladd & Howe 1997), at an angle of ~52° from the main CO flow, i.e., apparently unrelated to the second H₂ outflow. The ¹²CO emission indicates terminal velocities of 80 and ~125 km s⁻¹ in its north and south lobes, respectively, which implies a dynamical age of ~3 × 10⁷ yr, at a distance of 730 pc (Eislöffel et al. 1996). The absence of a second source in interferometric observations at 2.65 mm suggests that both outflows arise very close to the position of IRAS 23011+6126 (Ladd & Howe 1997).

In this study, we present new ISOCAM (Kessler et al. 1996; Cesarsky et al. 1996) images of the Cep E outflow taken in the ground vibrational level (v = 0–0) H₂ lines S(5), at 6.91 μm, and S(3), at 9.66 μm. The motivation of this work was to use the ground vibrational H₂ lines, which are predicted to be much brighter than the v = 1–0 S(1) line (Wolfire & Königl 1991), to study the excitation across the outflow [using the S(3)/S(5) ratio] and to try to detect the second H₂ outflow and the central source at mid-infrared wavelengths, as well as to search for traces of H₂ emission along the second CO outflow. These observations are complemented by IRAS HIRES images.

2. OBSERVATIONS

The Cep E outflow has a projected size onto the plane of the sky of ~1′, so the ISOCAM images were obtained using a 2 × 3 circular variable filter (CVF) raster map with a 6′ field of view pixel scale and 30′ steps. Four CVFs were used: two very close centered on the v = 0–0 S(3) 9.665 μm and S(5) 6.909 μm H₂ lines, respectively (see below), plus two nearby continuum CVF steps at 9.535 and 6.855 μm. We selected the S(3) 9.665 μm line, despite the fact that its wavelength is right in the middle of the strong silicate absorption feature at ~9.7 μm, because the line is expected to be strong and should help to constrain the depth of the silicate absorption in the models of the spectral energy distribution (SED).

The ISOCAM data were “deglitched” using the multi-resolution median transform method, as implemented in the CAM Interactive Analysis package. The detector’s transient effects were treated using the IPAC model (K. Ganga 1997,
private communication). The target-dedicated time (TDT) was 2728 s, with 12 stabilization time steps on line and 10 in the continuum prior to the on-target observations. The TDT was spent with two-thirds of the time on line and one-third in the continuum; this means approximately 900 s in each of the H$_2$ lines. The ADU fluxes were transformed into calibrated fluxes using the upgraded values of the system response (see, e.g., ISOCAM Observer’s Manual, Tables 12–17). These values are given in ADU s$^{-1}$ mJy$^{-1}$ pixel$^{-1}$ and correspond to 125.52 (step 227, 9.660 $\mu$m), 65.80 (step 331, 9.535 $\mu$m), 122.12 (step 21, 6.911 $\mu$m), and 121.686 (step 22, 6.855 $\mu$m). The FWHMs of the four filters are 0.27, 0.22, 0.17, and 0.17 for the 9.660, 9.535, 6.911, and 6.855 $\mu$m, respectively, and we used an integration time step of 2 s and an analog-to-digital converter gain of 2.

For comparison, we also present a near-infrared image in the $v = 1\rightarrow 0$ S(1) 2.12 $\mu$m line obtained at the Apache Point Observatory 3.5 m telescope with a 256 $\times$ 256 array at f/5 with a 0.482 pixel$^{-1}$ scale. A complete analysis of the imaging and spectroscopic near-infrared data is presented elsewhere (Ayala et al. 1998). IRAS HIRES images are also presented to support these observations. These images have a 1° field of view with 15” pixels and can reach a spatial resolution of $\sim$1’. The HIRES images have been processed using Y. Cao’s algorithm (see, e.g., Noriega-Crespo et al. 1997).

3. RESULTS

3.1. Morphology

The gray-scale images of H$_2$ at 9.66 and 6.91 $\mu$m are presented in Figures 1 and 2, respectively. From these images it is evident that the morphologies of these different molecular hydrogen lines are very similar. It is also clear that the main difference between them is the central intensity peak at 9.66 $\mu$m. This intensity peak coincides with the position of the IRAS 23011 + 6126 source, as determined using interferometric observations by Eisloffel et al. (1996), i.e., $\alpha = 23^\mathrm{h}03^\mathrm{m}13^\mathrm{s}$, $\delta = 61^\circ42’26.5”$ (J2000.0). IRAS 23011 + 6126 is also detected in the continuum frame at 6.855 $\mu$m, indicating that the emission is not dominated by the excited H$_2$ emission. Figure 3 shows the 6.91 $\mu$m image with an overlay of the H$_2$ 2.12 $\mu$m emission, and once again the morphologies of both molecular lines are very similar.

One way to understand these observations is in terms of the interstellar extinction law (see, e.g., Mathis 1990), which has a minimum at $\sim$ 7 $\mu$m and then rises to a peak at $\sim$10 $\mu$m, this maximum being due to the silicate absorption feature. If IRAS 23011 + 6126 is embedded in a dusty envelope, as expected for a Class 0 source, then the absorption by silicates will be even greater and enough to swamp the H$_2$ emission at 9.66 $\mu$m. IRAS 23011 + 6126 appears in all the IRAS bands, as is shown in Figure 4, which displays IRAS HIRES maps at 12, 25, 60, and 100 $\mu$m centered on Cep E.

Recall that another two outflows have been detected around Cep E. One outflow is observed in 2.12 $\mu$m H$_2$ emission and is almost perpendicular to the main H$_2$ flow. The second is detected in the $^{13}$CO $J = 2\rightarrow 1$ transition and is centered on IRAS 23011 + 6126 ($\pm 2’’3’’$), with an orientation of $\sim 52^\circ$ with respect to the main H$_2$ flow and a scale of $\sim 4’$ (Ladd & Hodapp 1997). We do not detect in the H$_2$ lines at 9.66 and 6.91 $\mu$m any signatures of the second H$_2$ outflow or of the second CO outflow observed at millimeter wavelengths. For the faint 2.12 $\mu$m H$_2$ outflow this perhaps is not surprising, since the S(3) 6.91 $\mu$m line would have to be $\sim 70$ times stronger than the S(1) 2.12 $\mu$m line (based on simple continuous [C-type] shock models; e.g., Smith 1995) to overcome its very low surface brightness in comparison with the brightest regions. We estimate that the rms noise levels of our ISOCAM images, based on measurements of the background, are approximately 46 $\mu$Jy arcsec$^{-2}$ at 9.66 $\mu$m and 12 $\mu$Jy arcsec$^{-2}$ at 6.91 $\mu$m. The values of the minimum contours in Figures 1b and 2b (continuum subtracted) are 0.4 and 0.2 $\mu$Jy arcsec$^{-2}$ for the 9.66 and 6.91 $\mu$m lines, respectively, so a factor of 70 decrease in brightness for the faint H$_2$ outflow is at the noise level. There are no traces in the IRAS HIRES images of the faint H$_2$ flow or of the CO outflow. The HIRES images do not resolve the second source near IRAS 23011 + 6126 either, as is shown in Figure 4. The 12 and 25 $\mu$m images in Figure 4 display only point sources, and although there is some faint emission at 60 and 100 $\mu$m at P.A. $\sim$ $-45^\circ$, this is probably due to the diffuse emission from the nearby sources. The existence of a second source 2” southwest from IRAS 23011 + 6126 has recently been confirmed by L. Testi (1998, private communication) with observations at the Owens Valley Radio Observatory at 1.3 mm.

3.2. Fluxes

As mentioned above, the $v = 0\rightarrow 0$ S(3) and S(5) H$_2$ lines were selected for our observations because plane-parallel molecular shock models predict, for the conditions encountered in HH objects, that these lines could be $\sim 10$–100 times stronger than the $v = 1\rightarrow 0$ S(1) 2.12 $\mu$m line if they are collisionally excited. Molecular shock models specifically calculated for HH objects (Wolff & Königl 1991) have considered as typical parameters, e.g., a shock velocity of $v_s = 25$ km s$^{-1}$, an initial preshock gas density of $n_0 = 10^5$ cm$^{-3}$ and a preshock magnetic field of $B_0 = 30$ $\mu$G, a molecular hydrogen abundance of $n_{\text{H}_2}/n \sim 0.5$, an atomic hydrogen abundance of $n_{\text{H}_2}/n \sim 3 \times 10^{-3}$, a neutral gas temperature of $T \sim 2000$ K, and an electron temperature of $T_e \sim 3000$ K. The point of enumerating some of these parameters (there are a few more) is to illustrate the difficulty in comparing shock models with observations and to stress that the models should be taken as a guide, since the physical conditions across a shock front change and are more complex.

For the input parameters of the shock models mentioned above, the expectation is that the ratios of the H$_2$ lines should be $0$–$0$ S(3)/$1$–$0$ S(1) $\sim 157$ and $0$–$0$ S(5)/$1$–$0$ S(1) $\sim 28$, or essentially $0$–$0$ S(3)/0–$0$ S(5) $\sim 5.6$. The ratio of our S(3) and S(5) H$_2$ images is shown in Figure 5, which indicates that the ratio across the outflow is nearly unity. The ratio is constant except in the region around IRAS 23011 + 6126, which is not detected in the S(5) 9.66 $\mu$m image, and at the edge of the outflow, which is probably the result of an artifact produced by the mismatch between the elliptical Gaussian function used to smear out the S(3) 6.91 $\mu$m image and the true shape of the first Airy ring produced by the ISOCAM optics.

Nearly constant distributions across the outflow have also been measured for the $2$–$1$ S(1)/$1$–$0$ S(1) and $3$–$2$ S(3)/ $1$–$0$ S(1) ratios (Eisloffel et al. 1996). This behavior is very difficult to explain with simple shock models or shock

See also http://isowww.estec.esa.nl/manuals/iso_cam/.
Fig. 1a

Fig. 1b

Fig. 1.—(a) Gray-scale image of the Cep E outflow in the $v = 0-0 S(3)$ $9.66 \, \mu m$ $H_2$ line (with continuum) in a $2' \times 2'$ field of view. (b) The same gray-scale image (continuum subtracted), with contours beginning at $0.4 \, mJy \, arcsec^{-2}$ and increasing by factors of $\sqrt{2}$. 

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Fig. 2a

Fig. 2b

Fig. 2.—Same as Fig. 1, but in the $\tau = 0$–$0$ $S(5) \, 6.91 \, \mu m$ $H_2$ line. Contours in (b) begin at 0.2 mJy arcsec$^{-2}$, and increase by factors of $\sqrt{2}$. 

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Fig. 3.—Gray-scale image of the $v = 0–0\, S(5)\, 6.91\, \mu m$ line (with continuum) with a linear contour map of the $v = 1–0\, 2.12\, \mu m$ emission superposed.

Fig. 4.—IRAS HIRES images at 12, 25, 60, and 100 $\mu m$ (top left to bottom right) centered on IRAS 23011 + 6126. The field is $1^\circ$, with the usual orientation, and the circle surrounding the IRAS source has a 5$'$ radius.
geometries, and in the case of the $v = 2-1$ $S(1)$ and $v = 3-2$ $S(3)$ line ratios, the best results have been obtained with C-type bow shocks. Such models needed shock velocities of $\sim 200$ km s$^{-1}$ and preshock densities of $\sim 10^6$ cm$^{-3}$ (Eisloffel et al. 1996), which are higher than what is measured in most optical outflows.

A constant $v = 0-0$ $S(3)$-to-$S(5)$ ratio also indicates the lack of a steep extinction gradient between the north and south lobes and that the extinction is mostly important around IRAS 23011+6126. This is interesting because we know that the south lobe is visible at optical wavelengths (Noriega-Crespo 1997), while the north lobe is not.

Finally, we have measured the flux of IRAS 23011+6126 at 6.855 $\mu$m, set an upper limit for the 9.535 $\mu$m flux (which may still be affected by the silicate feature), and measured the IRAS fluxes from the HIRES images. In Figure 6, we show the SED of the source, including the values obtained at 1.25 mm and 2.22 $\mu$m by Lefloch, Eisloeffel, & Lazareff (1996) and at 2.65 mm by Ladd & Howe (1997). We have overplotted (following Ladd & Howe 1997) four simple graybody models, at $T_{\text{dust}} = 10, 20, 30,$ and $40$ K, of the form $F_\nu = B_\nu(T)(1 - e^{-\tau}) \Omega_\nu$ with $\tau \propto \nu^{-2}$ and the optical depth.
normalized to the 2.65 mm flux. The simple models do a reasonable job at the IRAS and millimeter wavelengths for $T_{\text{dust}} = 20-30$ K but are unable to fit the shorter wavelengths.

It is possible to build more sophisticated models for the SED that include a density and temperature structure for the cloud core or an envelope that surrounds the Class 0 object (André & Montmerle 1994), and which also take into account the dust opacity as a function of chemical composition and wavelength (see Appendix). In Figure 7, we display three models that have different inner gas cloud core densities ($6 \times 10^4$, 8 $\times 10^4$, and $10^5$ cm$^{-3}$) but are otherwise identical in their input parameters. The model with an initial density of $8 \times 10^4$ cm$^{-3}$ (solid line) fits the observations amazingly well and is consistent with the upper limits at 2.22 and 9.855 μm, which are based on “no detections.” The models also illustrate how well they fit the IRAS and sub-/millimeter observations, and how sensitive they are to the presence of the ~20 μm silicate feature. This feature essentially disappears in the $6 \times 10^4$ cm$^{-3}$ model (dotted line) and, not surprisingly, becomes deeper with an increasing density at $10^7$ cm$^{-3}$ (dashed line).

The model SEDs in Figure 7 assume a dust opacity dominated by bare silicates—hence the strong absorption features at 10 and 20 μm—and a dust temperature of 18 K. The models consider power-law density and temperature distributions (see Appendix), with a core inner radius of 0.065 AU and outer radius of 0.1 pc. The total masses for the cloud envelope surrounding the IRAS source for the three models (increasing in density) are 13, 17, and 22 $M_\odot$. Our best model (with $T_{\text{dust}} = 18$ K and $M_{\text{env}} = 17$ $M_\odot$) yields different values from those obtained by using a constant density distribution and the simple graybody models, i.e., $T_{\text{dust}} = 20$ K and $M_{\text{env}} = 10$ $M_\odot$ (Ladd & Howe 1997).

4. CONCLUSIONS

We have analyzed some of the physical characteristics of the Cep E embedded outflow using ISO-CAM images in the $v = 0-0$ S(5) 6.91 μm and S(3) 9.66 μm molecular hydrogen lines. We find that the morphology of the Cep E outflow in the ground vibrational H$_2$ lines is similar to that of the near-infrared emission in the $v = 1-0$ 2.12 μm line. At these wavelengths, and at surface brightnesses of 12–46 μJy arcsec$^{-2}$, we do not detect the second H$_2$ outflow almost perpendicular to the main 2.12 μm flow, nor do we find traces of H$_2$ along the second $^{12}$CO J = 2–1 outflow, at an angle of ~52°.

We detect at 6.91 μm the likely source of the main H$_2$ and CO outflows, IRAS 23011+6126, and we showed that the source is well detected in all IRAS bands using HIRES images. The source is not detected at 9.66 μm (or at 9.54 μm), but we think that this agrees with the interstellar extinction curve, which has a minimum at ~7 μm but rises at ~9.7 μm as a result of the strong silicate absorption feature, further enhanced in this case by a cocoon surrounding the Class 0 object as the model of the SED seems to indicate.

The 0–0 S(3)/0–0 S(5) ratio is uniform and near unity across the outflow, a fact that is difficult to explain with simple plane-parallel shock models (Eislöffel et al. 1996). A constant S(3)-to-S(5) ratio also indicates that the extinction, with the exception of the vicinity of the IRAS 23011 +6126 source, is not affecting the H$_2$ emission of the outflow lobes at these wavelengths. Assuming that the main source of opacity around IRAS 23011 +6126 is due to bare silicates, then our best model SED for the envelope surrounding the Class 0 source yields a total mass of 17 $M_\odot$ and a dust temperature of 18 K.

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APPENDIX

The envelope around Cep E is modeled as a series of spherically symmetric dust shells, where temperature and density are assumed to vary according to radial power laws, the exponents of which are free parameters. Once the external radius of the envelope is fixed, the inner envelope boundary is also determined and is equal to the radius where dust attains its sublimation temperature (~1500 K). As our aim was not only to provide a reasonable model for the global spectral energy distribution of Cep E but also to determine whether the nondetection at 9.67 μm could be due to silicate absorption, we decided to adopt the dust opacities tabulated by Ossenkopf & Henning (1994) for an MRN (Mathis, Rumpl, & Nordsieck 1977) silicate dust with variable volumes of ice mantles, instead of the usual assumption (e.g., Hildebrand 1983) of a dust opacity simply expressed as a power law in frequency.
Dust emission is computed from each shell as
\[ F_{v,i} = \kappa_i B(v, T_i) \rho_i V_i, \]  
(A1)
where \( \kappa_i \) is the dust mass opacity, \( B(v, T_i) \) is the Planck function, \( \rho_i \) is the density, and \( V_i \) is the volume of the \( i \)th shell. First, for each frequency the optical depth is computed inward as \( \tau = \int \kappa_i \rho_i \, dr_i \) until either \( \tau = 1 \) is eventually reached for a certain shell or the inner envelope radius is reached; having identified the inner shell that contributes to observed radiation, the emitted flux is computed outward according to equation (A1) until the external radius is reached. The flux from each shell is extincted by the intervening shells toward the observer, and finally the contributions from all shells are summed at each frequency.

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