INFRARED AND MILLIMETRIC STUDY OF THE YOUNG OUTFLOW CEPHEUS E

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ABSTRACT

The Cepheus E outflow has been studied in the mid- and far-IR using the ISOCAM and Long Wavelength Spectrometer (LWS) instruments and at millimetric wavelengths using the Owens Valley Radio Observatory (OVRO). In the near- and mid-IR, its morphology is similar to that expected for a jet-driven outflow, where the leading bow shocks entrain and accelerate the surrounding molecular gas. As expected, fine-structure atomic/ionic emission lines arise from the bow shocks, at both the Mach disk and the stagnation tip, where J-shocks are dominant. The $\text{H}_2$, $\text{H}_2\text{O}$, and CO molecular emission could arise farther “downstream” at the bow shock wings where the shocks ($v \approx 8-35$ km s⁻¹) are oblique and more likely to be C-type. The $^{13}\text{CO}$ emission arises from entrained molecular gas, and a compact high-velocity emission is observed, together with an extended low-velocity component that almost coincides spatially with the $\text{H}_2$ near-IR emission. The millimetric continuum emission shows two sources. We identify one of them with IRAS 23011+6126, postulating that it is the driver of the Cepheus E outflow; the other, also an embedded source, is likely to be driving one of the other outflows observed in the region. Finally, we suggest that the strong [C II] 158 μm emission must originate from an extended photodissociation region, very likely excited by the nearby Cepheus OB3 association.

Subject headings: infrared: ISM — ISM: jets and outflows — stars: formation — stars: pre—main-sequence

1. INTRODUCTION

Low-mass protostars produce outflows that interact mostly through shocks with the surrounding medium (e.g., Reipurth & Raga 1999). Nevertheless, the details of the earliest evolutionary steps remain somewhat unclear. The embedded flow at Cepheus E (hereafter Cep E) displays all the characteristics of an extremely young object still surrounded by a thick cocoon of cold gas (e.g., Cernicharo et al. 2000) and hence provides an ideal opportunity to study the development of molecular/ionic outflows and their surrounding environments during the earliest stages of star formation.

Cep E was identified originally as a cloud core in molecular CO observations (Sargent 1977), and subsequently, an associated outflow was discovered (see Fukui 1989; Hodapp 1994). The region around Cep E has proved more complicated than the early CO and the K’ observations indicated; there are at least two other outflows besides the original compact “north-south” $\text{H}_2$ flow identified by Ladd & Hodapp (1997). One is nearly perpendicular to the main $\text{H}_2$ flow and appears as a faint chain of $\text{H}_2$, 1−0 S(1) 2.121 μm emission knots toward the west (Eislöffel et al. 1996); the other is seen in the CO J = 1−0 line and is extended by $\sim 90^\circ$ along P.A. $\sim -45^\circ$ (Ladd & Howe 1997). All three flows arise within a 5° region around IRAS 23011+6126, which presumably encompasses the driving source (Lefloch, Eislöffel, & Lazareff 1996; Noriega-Crespo, Garnavich, & Molinari 1998; Cernicharo et al. 2000). For a low-mass object IRAS 23011+6126 is estimated to have a very high bolometric luminosity, $\sim 70 L_\odot$ (Lefloch et al. 1996), suggesting that we are dealing with a relatively massive protostar, or with a low-mass protostar in an unusually early evolutionary phase and considerably higher accretion luminosity.

The blueshifted south lobe of the original $\text{H}_2$ Cep E outflow is observed at optical wavelengths as HH 337, in the shock-excited Hz and [S II] $\lambda 6717/31$ emission lines (Noriega-Crespo 1997; Devine, Reipurth, & Bally 1997). This collisionally excited emission is characteristic of an extremely low excitation HH object ($\sim 1\%$ ionization) with an anomalously high electron density, $n_e \sim 4100$ cm⁻³, leading to an unusually high preshock density of $\sim 10^3$ cm⁻³ (Ayala et al. 2000, hereafter A00). Both the Hz and [S II] emission can be modeled using a J-shock of $v_{\text{shock}} \sim 15-30$ km s⁻¹ (A00), although the near-IR $\text{H}_2$ spectra agree better with C-shock models with $v_{\text{shock}} \sim 35$ km s⁻¹ (Ladd & Hodapp 1997). It has been suggested that a Mach disk produces the optical emission while the IR emission arises from a bow shock (A00).

Some of the first three-dimensional simulations of molecu-
ular jets were intended to model the complex structure of the H$_2$ Cep E outflow (Suttner et al. 1997). Surprisingly, they demanded relatively large (greater than $10^5$ cm$^{-3}$) densities, which could be a sign of a very early stage of jet development. This interpretation is consistent with the estimated dynamical age of the Cep E outflow, $\sim 3 \times 10^3$ yr (Eislöffel et al. 1996), assuming a distance of 730 pc. The above argument sets a scene in which Cep E is a very young outflow breaking through its placental molecular core.

Our new observations from the Infrared Space Observatory$^1$ (ISO) and the Owens Valley Radio Observatory (OVRO) millimeter-wave array at far-IR/mid-IR and millimetric wavelengths at higher sensitivity and spatial resolution permit not only a probe of deeper regions of the molecular environment surrounding the outflow but also a determination of the main excitation and cooling mechanisms. Both are essential to understanding the dynamical evolution of very young protostellar objects.

In §§ 2 and 3 we describe the ISO and OVRO observations and data reduction procedures, respectively. The infrared results are presented in § 4 and further analyzed in § 5, where we derive the gas physical parameters (such as temperature, density, column density, and size of the emitting region) and study the origin of this emission through J- and C-shocks and photodissociation regions (PDRs). In § 6 we analyze the millimeter results, using the $^{13}$CO line emission to derive such physical parameters of the outflow as dynamical timescale, mass and mass-loss rate, and continuum observations to provide an alternate estimate of the mass of the source. The source spectral energy distribution (SED) is examined in § 7, and in § 8 we summarize our results.

2. ISO OBSERVATIONS AND DATA REDUCTION

The Cep E outflow has been observed with two ISO instruments, the Long Wavelength Spectrometer (LWS; Clegg et al. 1996) and the infrared camera (ISOCAM; Cesarsky et al. 1996). The observations were taken during revolutions 566 (LWS: TDT 56,601,113 and 56,600,912) and 792 (ISOCAM: TDT 79,200,740). The LWS01 grating mode was used to acquire low-resolution ($R \sim 200$) spectra from 43 to 197 $\mu$m at two different locations along the flow [$\alpha(2000) = 23^h03^m13^s11, \delta(2000) = 61^\circ42'59.5"$ for the north lobe and $\alpha(2000) = 23^h03^m12^s73, \delta(2000) = 61^\circ41'56.5"$ for the south lobe]. Figure 1 shows the two pointing positions. These spectra are made up of 11 full grating scans over-

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$^1$ ISO is an ESA project with the instruments funded by ESA Members States (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom) and with the participation of ISAS and NASA.
sampled at one-fourth of a resolution element (equivalent to \( \sim 0.07 \) \( \mu m \) for \( \lambda < 90 \) \( \mu m \) and \( \sim 0.15 \) \( \mu m \) for \( \lambda > 90 \) \( \mu m \)). The integration time per spectral element was 22 s, corresponding to a total integration time of 1890 s per pointing. The LWS beam is assumed to be \( \sim 80^\circ \) in diameter (ISO Handbook,\(^4\) iv, 4.3.2). The ISOCAM (Cesarsky et al. 1996) observations were taken using the circular variable filter (CVF) with a total field of view (FOV) of 3', and pixel FOV of 6' centered on IRAS 23011+6126 \( [\alpha(2000) = 23^{h}03^{m}13^{s}, \delta(2000) = 61^\circ42'26''] \). The CVF spectra covered the 5.01–16.77 \( \mu m \) wavelength range with a resolving power of \( \sim 40 \). Each wavelength was observed for \( \sim 23 \) s, for a total on-source observing time of 3550 s.

The LWS Interactive Analysis\(^3\) (LIA) Package, Version 7.2, was used to correct the detector dark currents and drifts. Corrected and scan-averaged spectra were then analyzed using the ISO Spectral Analysis Package\(^4\) (ISAP), Version 2.0. Likewise, the ISOCAM-CVF data were reduced using the Cam Interactive Analysis\(^5\) (CIA) standard procedures, and spectra from the individual pixels were extracted using XCVF (B. Ali 2000, private communication) and further analyzed with ISAP.

### 3. MILLIMETER OBSERVATIONS AND DATA REDUCTION

High-resolution millimeter interferometric observations were obtained during 1997 and 2000 using the OVRO millimeter-wave array. The array comprises six 10.4 m antennas that were deployed in three different configurations offering baselines extending from the shadowing limit to 220 m. To ensure the best possible sensitivity to the extended outflow emission, the data from the most compact available configuration are included. Each telescope is equipped with cryogenically cooled SIS receivers providing typical system temperatures of \( \sim 300 \) K at 110 GHz and \( \sim 1200 \) K at 222 GHz. Continuum observations employed an analog correlator for total bandwidths of \( \sim 2 \) and 1 GHz at 222 and 110 GHz (1.3 and 2.7 mm), respectively. The digital correlator was configured to observe simultaneously the \(^{12}\)CO(1–0) and \(^{18}\)O(1–0) transitions at 110.2 and 109.8 GHz, respectively. For the former isotopomer, spectral resolution was 1.3 km s\(^{-1}\) over an \( \sim 80 \) km s\(^{-1}\) bandwidth, and for the latter, it was 0.3 km s\(^{-1}\) over \( \sim 20 \) km s\(^{-1}\). The half-power beamwidth is \( \sim 65^\circ \) at 110 GHz and \( \sim 33^\circ \) at 222 GHz.

| Map                  | Beam Size (arcsec) | P.A. (deg) | rms Noise (1 \( \sigma \)) |
|----------------------|-------------------|------------|---------------------------|
| 110 GHz (cont.)      | 3.1 x 2.8         | -86        | 1\(^a\)                   |
| 222 GHz (cont.)      | 1.4 x 1.0         | -78        | 7\(^b\)                   |
| \(^{18}\)O (1–0)     | 8 x 7             | 63         | 0.05\(^b\)                |
| \(^{13}\)CO (1–0)    | 8 x 7             | 54         | 0.03\(^b\)                |

\(^{a}\) In mJy beam\(^{-1}\).

\(^{b}\) In Jy beam\(^{-1}\) channel\(^{-1}\).

Complex gain calibration was ensured by frequent observations of the quasar BG 0059+58 (= [MFN99] 0059+581). The typical observing cycle alternated scans on Cep E and BG 0059+58 with a period of \( \sim 20–30 \) minutes. 3C 345 and/or 3C 84 were used as passband calibrators, while scans on Uranus and/or Neptune were used to set the flux scale. The expected flux calibration uncertainty is \( \sim 15\% \) at 2.7 mm and \( \sim 20\%–30\% \) at 1.3 mm. Data calibration and editing have been performed using the OVRO-MMA software package (Scoville et al. 1993). Imaging and analysis of the calibrated \((u, v)\) data sets were carried out with the AIPS IMAGR task using natural weighting of the \((u, v)\) data for the molecular outflow maps and the low spatial resolution continuum maps, while “ROBUST = 0” weighting was used for the 1.3 mm high-resolution map. The beam sizes and noise levels for the OVRO observations are shown in Table 1.

### 4. ISO RESULTS

#### 4.1. ISO-LWS

Figure 2 shows the LWS far-IR spectra obtained at the two pointing positions. The strongest features are the atomic fine-structure lines of [O I] 63 \( \mu m \) and [C II] 158 \( \mu m \). However, the spectra are also rich in molecular lines from the rotational transitions of CO and H\(_2\)O (in both ortho and para form). Two OH lines are also detected in the spectra, but they are too faint to be included in the analysis.

Integreated line fluxes, measured using a Gaussian fit, are shown in Table 2, with 1 \( \sigma \) uncertainties given in parentheses. In some cases the FWHM was kept fixed to the corresponding instrumental resolution element (i.e., 0.29 and 0.6 \( \mu m \) for the short-wavelength [SW] and long-wavelength [LW] detectors, respectively). This technique was particularly important in the case of faint and/or blended lines. The uncertainties were obtained either by using ISAP estimated values from the Gaussian fit or by adopting the rms of the fitted baseline times the resolution element. As expected, both values are very similar.

#### 4.2. ISOCAM CVF

ISOCAM CVF provides spectra covering the 5–17 \( \mu m \) range over a 32 x 32 pixel area. Each plane of the cube corresponds to a different \( \lambda \). Figure 1 shows, as was previously noticed by Noriega-Crespo et al. (1998), how the morphology at 2 and 7 \( \mu m \) in the H\(_2\) emission is quite similar. A more detailed description of the CVF emission at each pixel is given in Figure 3. Except at the source position (pixel [16, 16]), the 5–16 \( \mu m \) spectra are dominated by the H\(_2\) ground rotational lines from S(7) to S(2). Integrated line fluxes can be found in Table 3. These are corrected for extinction, using an estimated \( E(B - V) = 1.0 \) (Lefloch et al. 1996; A00) and the extinction curve from Draine (1989). The central source is clearly detected and displays strong silicate absorption at 9–12 \( \mu m \) and CO\(_2\) ice at 15.2 \( \mu m \) and a number of ice bands (see also Cernicharo et al. 2000). Figure 4 displays the images corresponding to the H\(_2\) 0–0 S(2)–S(7) lines. In accord with expectations based on ground-based optical and H\(_2\) observations at 2 \( \mu m \), the south lobe is brighter at shorter wavelengths, as the flow breaks through the cloud. The north lobe, buried deeper in the cloud, has fainter S(3) 9.66 \( \mu m \) and S(2) 12.28 \( \mu m \) emission, probably as a result of the broad second maxima at 9.7 \( \mu m \) due to

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\(^2\) Available at http://www.iso.vilspa.es/users/handbook.

\(^3\) LIA is available at http://www.ipac.caltech.edu/iso/ls/ia/ia.html.

\(^4\) ISAP is available at http://www.ipac.caltech.edu/iso/isap/isap.html.

\(^5\) CIA is available at http://www.ipac.caltech.edu/iso/cam/cam_tools.html.
silicate (Si—O) stretch mode in the extinction curve (Draine 1989; Mathis 1990).

5. DISCUSSION

5.1. The Gas Physical Parameters

5.1.1. CO and H$_2$O Emission

The CO and H$_2$O emission can be studied by means of a large velocity gradient (LVG) model in spherical geometry, taking into account the first 35 rotational levels of CO and the first 30 rotational levels of ortho-H$_2$O. The collisional rates of Schinke et al. (1985) were used for CO and those of Green, Maluendes, & McLean (1993) and Phillips, Maluendes, & Green (1996) for H$_2$O.

There are six main parameters to fit: temperature ($T$), H$_2$ density [$n$(H$_2$)], CO and ortho-H$_2$O column densities [$N$(CO) and $N$(ortho-H$_2$O)], intrinsic width of the line ($v_{\text{exp}}$), and angular size of the emitting area ($\Omega$). To determine all of them simultaneously, two initial assumptions are necessary: (1) the CO and ortho-H$_2$O emission arises from the same region, and (2) the CO lines are optically thin, i.e., their line fluxes do not depend on their intrinsic widths, while the ortho-H$_2$O lines are optically thick. Since the LWS resolution is too poor to establish size and position of the emitting region, it is difficult to justify assumption (1) from our data. However, in a 15'' beam, the H$_2$O emission in HH 7-11 appears to arise from the shocked regions already seen in the CO emission bullets (Cernicharo, Gonzalez-Alfonso, & Bachiller 1996; Bachiller & Cernicharo 1990). The adoption of assumption (2) will be confirmed by our models. Figure 5 shows the CO line fluxes as a function of the rotational quantum number, $J_{\text{up}}$, for Cep E north and south lobes. The shape of the distribution is determined only by $T$ and $n$(H$_2$), while the absolute fluxes are determined by $T$, $n$(H$_2$), and $\Omega N$(CO), which is proportional to the total number of CO molecules within the emitting volume.

Two extreme cases for each lobe are consistent with the observations. All the models predict that the CO lines are effectively optically thin. Figure 5 shows that the agreement is good for $J_{\text{up}} < 22$, but for higher $J_{\text{up}}$ the models underestimate the observed fluxes. This could indicate the existence of a hotter CO gas component as suggested by Spinoglio et al. (2000) for T Tauri.

Assuming that the CO and the ortho-H$_2$O line emission is from the same gas, the temperatures and densities derived from the CO lines can be used to model the ortho-H$_2$O line fluxes. Since these lines are optically thick, their absolute fluxes depend on all the free parameters in the model, $T$, $n$(H$_2$), $N$(ortho-H$_2$O), $v_{\text{exp}}$, and $\Omega$. Their relative fluxes (or line ratios), on the other hand, do not depend on $\Omega$. Thus, with $T$ and $n$(H$_2$) known, the line ratios were modeled and the values of $N$(ortho-H$_2$O) and $v_{\text{exp}}$ were constrained. Models of the absolute fluxes then allowed a derivation of $\Omega$. The ortho-H$_2$O lines at 179, 174, 113, and 75 $\mu$m were used because they have the highest signal-to-noise ratio and because the ortho-H$_2$O 179 $\mu$m/174 $\mu$m ratio is very sensitive to $T$ and $n$(H$_2$).

A summary of the LVG model parameters consistent with the observations can be found in Table 4. A comparison between the LVG models for ortho-H$_2$O and the observations is shown in Figure 5. The diameter range estimated
for the ortho-H$_2$O emitting region is comparable to the extension of the vibrational H$_2$ 1–0 (S1) 2.12 $\mu$m emission, 2700–6900 AU (3.7–9.5) at a distance of 730 pc. Knowing the emitting area, we calculate N(CO) and hence the H$_2$O/H$_2$ abundance ratio, assuming a standard value of CO/H$_2$ $\approx 10^{-4}$ in shock regions. For H$_2$O, an ortho/para ratio of 3 was adopted, leading to predicted para-H$_2$O fluxes within 3 $\sigma$ of the observed values. The low-temperature models give H$_2$O/H$_2$ $\approx 4.0 \times 10^{-5}$ and $1.5 \times 10^{-5}$ for the north and south lobes, respectively. The high-temperature models give H$_2$O/H$_2$ $\approx 2.5 \times 10^{-4}$ (north) and $2.4 \times 10^{-4}$ (south). Taking into account these estimates together with their uncertainties, it can be concluded that H$_2$O abundances are between 100 and 4000 times greater than expected for the ambient medium in cold quiescent conditions, x(H$_2$O) $\approx 10^{-7}$ (Bergin, Melnick, & Neufeld 1998; Moneti, Cernicharo, & Pardo 2001), a result commonly found in young stellar objects (Liseau et al. 1996; Cernicharo et al. 1996; Harwit et al. 1998; Gonzalez-Alfonso et al. 1998; Ceccarelli et al. 1999; Spinoglio et al. 2000). This significant enhancement in the water abundance within outflow regions can be attributed to the vaporization of volatile grain mantles and the increased rate coefficients for specific gas-phase reactions at the elevated gas temperatures reached behind the shocks, and it is expected to persist for $\sim 10^5$ yr (Bergin et al. 1998).

According to the LVG models, the high-J CO emission detected by ISO-LWS indicates a temperature between 220 and 1200 K. Since the contribution to low-J emission from gas at such temperatures is negligible, the ISO observations must be tracing only the hottest shocked molecular material. By contrast, millimetric observations of the low-J emission ($J = 2$–1, Lefloch et al. 1996; $J = 4$–3, Hatchell, Fuller, & Ladd 1999) provide information about the entrained gas.

### 5.1.2. H$_2$ Emission

The pure rotational H$_2$ lines seen in the ISO/CAM CVF spectra arise from quadrupole transitions that are always optically thin. Because of their low Einstein coefficients, thermalization is readily possible for moderate volume...

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**TABLE 2**

| Parameter | North | South |
|-----------|-------|-------|
| Temperature (K) | 220, 1200 | 215, 1200 |
| $n$(H$_2$) (10$^6$ cm$^{-3}$) | 2.0, 0.02 | 4.0, 0.04 |
| $v_{exp}$ (km s$^{-1}$) | 20–40, 25–40 | 30–40, 15–60 |
| Source diameter (arcsec) | 5.1–3.7, 5.7–4.3 | 5.8–5.1, 9.5–4.7 |
| $N_{CO}$ (10$^{17}$ cm$^{-2}$) | 9.5–18.0, 16–26 | 7.3–9.3, 2.8–11.3 |
| $N_{H_2}$ (10$^{17}$ cm$^{-2}$) | 3–5, 30–50 | 0.8–1.0, 5–20 |
| $N_{H_2}$ (10$^{18}$ cm$^{-2}$) | 1–1.7, 10–16.7 | 0.27–0.3, 1.7–6.7 |
| $L_{CO}$ (10$^{15}$ W cm$^{-2}$) | 2.1, 2.6 | 2.4, 2.8 |
| $L_{p-H_2}$ (10$^{18}$ W cm$^{-2}$) | 1.8, 2.1 | 1.3, 2.1 |
| $L_{p-H_2}$ (10$^{18}$ W cm$^{-2}$) | 0.6, 0.6 | 0.4, 0.6 |

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**TABLE 3**

| Line | North | South |
|------|-------|-------|
| S(7) | 5.51... | 3.90(0.6) | 4.3(0.5) | 2.00(0.3) | 2.3(0.3) | 7.5(0.5) | 4.1(0.2) | 1.5(0.3) |
| S(6) | 6.11... | 3.10(0.5) | 3.3(0.4) | 1.00(0.2) | 0.9(0.2) | 4.1(0.2) | 2.2(0.3) | 1.5(0.3) |
| S(5) | 6.91... | 5.70(2.3) | 7.2(0.3) | 3.80(2.2) | 5.1(0.3) | 12.7(0.6) | 6.5(0.3) | 3.3(0.1) |
| S(4) | 8.02... | 3.50(2.2) | 4.2(0.2) | 2.00(0.2) | 1.4(0.2) | 2.6(0.2) | 1.8(0.1) | 1.6(0.1) |
| S(3) | 9.66... | 2.50(2.2) | 4.3(0.2) | 3.20(1.1) | 1.9(0.1) | 5.2(0.3) | 3.8(0.2) | 1.9(0.1) |
| S(2) | 12.28... | 2.00(2.2) | 4.0(0.3) | 3.1(0.2) | 1.4(0.1) | 1.9(0.2) | 1.6(0.2) | 1.3(0.2) |

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**TABLE 4**

| Parameter | North | South |
|-----------|-------|-------|
| $m$-H$_2$O | 0.6, 0.6 | 0.4, 0.6 |

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* Fluxes dereddened by $E(B-V) = 1.0$, in units of $10^{-11}$ W cm$^{-2}$ sr$^{-1}$. 

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**Note:** Horizontal dotted lines indicate nondetections.

* $\sigma$ uncertainties are given in parentheses.

* FWHM was fixed at 0.29 $\mu$m.

* Blended with CO 29–28 90.16 $\mu$m.

* FWHM was fixed at 0.60 $\mu$m.

* Blended with p-H$_2$O 2$_{12}$–1$_{12}$, 100.98 $\mu$m.

* Blended with CO 23–22 137.6 $\mu$m.
Fig. 3.—ISOCAM-CVF observations of Cep E outflow. In gray scale is the $\text{H}_2$ 0–0 S(5) 6.91$\mu$m image. Superimposed are the background-subtracted spectra obtained at several positions along the outflow. Their scale is identical to that of the two magnified spectra shown in the upper left, for one position in the south and one in the north lobe. The spectrum at the central source position, IRAS 23011 + 6126, is shown in the lower right on a different scale. Below it is the spectrum of the background averaged over 100 pixels. Orientation and pixel size are indicated in the figure.
densities. Hence, LTE calculations are precise enough to compute H$_2$ column densities. In outflows from YSOs, the H$_2$ emission is mostly produced by collisional excitation driven by shocks, but to gain some insight into the overall nature of the gas, LTE is commonly assumed. It is then possible to estimate the excitation temperature ($T_{ex}$) and column density of the gas using:

$$\ln \left( \frac{N_j}{g_j} \right) = \ln \left( \frac{N_{tot}}{Q} \right) - \frac{E_j}{kT_{ex}}$$

where $A_j$ is the transition probability (Turner, Kirby-Docken, & Dalgarno 1977) and $E_j$ the energy of the upper level (in cgs units) (Dabrowski 1984). The dereddened fluxes, $F_j/\Omega$, are listed in Table 3. The partition function ($Q$) was calculated assuming an ortho-para ratio of 3. The excitation diagrams $\ln (N_j/g_j)$ versus $E_{up}$ and the derived excitation temperatures and column densities for several pixels along the flow are shown in Figure 6. A single-component model predicts the intensities from the S(3) to the S(7) lines very well, but the intensity of S(2) is systematically underestimated.

5.2. Interpreting the Shock-excited Emission

5.2.1. C-Shocks

The ground rotational H$_2$ emission observed in YSOs is mostly attributed to collisional excitation from shocks, either C-type or J-type (Draine & McKee 1993). In a nutshell, C-type shocks are inherently magnetic and less harsh on molecules because Alfvénic waves prepare the gas to the hydrodynamic shock. J-type shocks are mostly hydrodynamic and can dissociate H$_2$ molecules at lower shock velocities. In the mid-IR and far-IR, where molecular transitions are detected, C-type shocks are expected to be more important. This is confirmed by the comparison of the CO and H$_2$ pure rotational line fluxes predicted by C-shock models for $v_{shock}$ $\sim$ 10–40 km s$^{-1}$ and gas densities $10^4$–$10^6$ cm$^{-3}$ (Kaufman & Neufeld 1996), and J-shock models for $v_{shock}$ $\sim$ 30–150 km s$^{-1}$ and the same gas density range (Hollenbach & McKee 1989). C-shock fluxes are at least 10 times brighter than the J-shocks (and this factor can be much larger depending on the shock conditions). A similar situation is expected for H$_2$O, and the following analysis assumes that only C-shocks contribute.

The shock velocity and preshock density are estimated using the pure rotational H$_2$ line fluxes and their ratios. From a comparison of these values with C-shock models (Kaufman & Neufeld 1996), we determine a range of 20–40 km s$^{-1}$ shock velocities, but over a wide range of preshock gas densities. The $v_{shock}$ value of $\sim$ 35 km s$^{-1}$ derived from the near-IR H$_2$ emission lines (Ladd & Hodapp 1997) falls within this range. An estimate of the preshock gas density can be obtained with the additional assumption that the emission from the pure rotational H$_2$ and CO lines arises from the same region. If so, the CO/H$_2$ cooling ratio can be used in conjunction with the shock velocities. Since this ratio encompasses all cooling, the fraction of lines lying outside the LWS and CVF wavelength coverage must be taken into account. The CO, ortho-H$_2$O, and para-H$_2$O cooling rates derived from the LVG models can be found in Table 4. For CO, the LVG models neglect the contribution from lines with $J_{up} > 22$, which may belong to a hotter
component. The H$_2$ cooling was estimated using the simple LTE model and, after taking into account the difference between the LWS and ISOCAM beam, is $1.6 \times 10^{-18}$ W cm$^{-2}$ for both the north and south lobes. Figure 7 shows the comparison between the corrected CO/H$_2$ cooling ratios and those predicted by C-shock models (Kaufman & Neufeld 1996). Within the $v_{\text{shock}}$ range of 20–40 km s$^{-1}$, the models predict a preshock density of $10^4$–$2.5 \times 10^5$ cm$^{-3}$.

Figure 8 shows the predicted CO/H$_2$O cooling ratio as a function of preshock density and shock velocity for C-shock models (Kaufman & Neufeld 1996). The observed (and corrected) ratio for the Cep E outflow indicates shock velocities of 8–14 km s$^{-1}$, inconsistent with the values derived from the CO/H$_2$ ratios. This could be due to the fact that the brightest emission regions in H$_2$ and CO do not seem to coexist spatially, as has been assumed, and therefore trace different gas conditions. Indeed, $^{13}$CO presented in Figure 9 suggests that this may be the case. We discuss this further below. The spatial resolution available with LWS and ISOCAM spectra prevents further discrimination between shock diagnostics.

5.2.2. J-Shocks and Photodissociation Regions

The integrated fluxes of the [O I] 63 $\mu$m and [C II] 158 $\mu$m emission are comparable for both the north and south outflows (see Table 2). Since the strength of the [C II] line predicted by shock models is several orders of magnitude fainter than the [O I] line, a fraction of the cooling is due to the presence of a PDR (Hollenbach & Tielens 1999). Most of the [O I] 63 $\mu$m emission is expected to be produced by shock excitation, but a percentage comes from a PDR. And so, to best use the [O I] 63 $\mu$m and [C II] 158 $\mu$m lines as diagnostics of the PDR parameters, an estimate of the [O I] collisional fraction is necessary. For this, we use the additional information provided by the optical forbidden atomic lines (e.g., [O I] $\lambda\lambda$6300, [S II] $\lambda\lambda$6717/31) and that they are generated by J-shocks, very likely at the Mach disk (A00). Implicitly, we are assuming that the molecular emission arises at the bow shock wings, where C-shocks dominate the emission.

Near-IR and optical observations suggest a range of J-type shock velocities of 15–35 km s$^{-1}$. Assuming $v_{\text{shock}} = 30$ km s$^{-1}$, the predicted ratio of [O I] 63 $\mu$m to [O I] $\lambda\lambda$6300 is $\sim 10$ for $n = 10^{5}$ cm$^{-3}$ (Hollenbach & McKee 1989). Since the observed [O I] $\lambda\lambda$6300 flux from the south lobe is $4.7 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, the predicted [O I] 63 $\mu$m flux over the entire object ($r \sim 2.5$) is $9.2 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$. This is of order $\sim 25\%$ lower than the LWS flux of $12 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$. From a comparison of J-shock and C-shock models (see Hollenbach & McKee 1989; Draine, Roberge, & Dalgarno 1983; Timmermann 1998), we estimate that at $n = 10^{5}$ cm$^{-3}$ the contribution of C-shocks to the [O I] 63 $\mu$m flux is about 5%–10% that of J-shocks. We will assume that about $\sim 20\%$ of the [O I] 63 $\mu$m flux corresponds to the PDR component. However, the percentage drops as the shock velocity decreases, and indeed for $v_{\text{shock}} = 20$ km s$^{-1}$, the collisional emission matches the observed LWS flux. The corrected ratio of [O I] 63 $\mu$m to [C II] 158 $\mu$m emission is then 0.30. With the corrected value of [O I] 63 $\mu$m/[C II] 158 $\mu$m and the observed LWS [C II] flux of $6.8 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$, PDR models can be used to determine the far-ultraviolet (FUV) flux and gas densities required to reproduce the observations. Two of the models of Kaufman et al. (1999) satisfy the above constraints. For one, the incident FUV flux in units of $1.6 \times 10^{-3}$ ergs s$^{-1}$ cm$^{-2}$, $G_0$, is 30, at a density of 60 cm$^{-3}$, while for the other, $G_0 = 6$, at a density of 5500 cm$^{-3}$.

The integrated flux in the polycyclic aromatic hydrocarbon (PAH) bands (e.g., at 6.2, 7.7, and 11.3 $\mu$m) is correlated with the FUV radiation field (Boulanger et al. 1998). Thus, the existence of a global FUV field can be indirectly inferred from the presence of extended PAH emission over the entire FOV of the CVF ISOCAM observations (see Fig. 3). However, the PAH emission could arise anywhere along the line of sight to Cep E.

Cep E is near the Cep OB3 association (Sargent 1977) with members at distances of 500–1000 pc (Crawford &
6. RESULTS FROM THE MILLIMETRIC OBSERVATIONS

6.1. \(^{13}\)CO Emission

The Cep E outflow can clearly be seen in the \(^{13}\)CO \(J = 1-0\) transition at 110.2 GHz, shown in Figure 9. One of the most interesting features of this figure is how the \(^{13}\)CO emission is almost bounded by the \(H_2\) outflow lobes, except at the edge of the south flow, which is breaking through the molecular cloud. Similar behavior is observed for the high-velocity CO gas in the HH 211 embedded outflow (Gueth & Guilloteau 1999, Fig. 4) and in HH 1/2 (Moro-Martín et al. 1999, Fig. 2c).

In LTE approximation, using an excitation temperature of 20 K (Ladd & Hodapp 1997), an abundance of \(^{13}\)CO/\(H_2\) \(\sim 1.2 \times 10^{-6}\), and an inclination angle of 45°, the following parameters are derived for the redshifted and blueshifted outflow lobes, respectively: dynamical timescales of 4000 and 8000 yr, masses of 0.08 and 0.05 \(M_\odot\), kinetic luminosities of 0.1 \(L_\odot\) for both, and mass-loss rates of \(7 \times 10^{-6}\) and \(6 \times 10^{-6} \ M_\odot \ yr^{-1}\). Nevertheless, these estimates are quite uncertain as a result of spatial filtering problems, core contamination, and the fact that the edges of the outflow are more than 20° from the phase center of the map and thus affected by primary beam attenuation.

Figure 10 shows a position-velocity diagram along the outflow axis (P.A. = 10°) with the ambient cloud at \(-11\) km s\(^{-1}\) and the outflow extending approximately from 0 to \(-20\) km s\(^{-1}\). Faint (2 \(\sigma\)) emission is also seen at \(-30\) and \(-40\) km s\(^{-1}\). We may be tracing high-velocity gas that is concentrated nearer to the source than its low-velocity counterpart. The left panels of Figure 11 show the emission...
Fig. 7.—CO/H$_2$ (rotational) cooling ratio (gray scale) as a function of preshock density and shock velocity for C-shock models [with $B = (n_H/cm^{-3})^{1/2} ~ \mu G$; Kaufman & Neufeld 1996]. The coolings obtained from the 200 and 1200 K LVG models for Cep E north and south lobes are shown in dashed and dotted lines, respectively. Contour levels are from 0 to 6.4 by 0.4.

Fig. 8.—CO/H$_2$O cooling ratio (gray scale) as a function of preshock density and shock velocity for C-shock models [with $B = (n_H/cm^{-3})^{1/2} ~ \mu G$; Kaufman & Neufeld 1996]. The coolings obtained from the 200 and 1200 K LVG models for Cep E north and south lobes are shown in dashed and dotted lines, respectively. Contour levels are from −1 to 2.25 by 0.25.

Fig. 9.—Superposition of the H$_3$ 1–0 S(1) 2.12 μm emission (gray scale) on the $^{13}$CO and 222 GHz continuum in contours. The dashed contours toward the north correspond to the redshifted lobe ($v_{LSR} = -9.5$ to $-2.5$ km s$^{-1}$), while the solid contours to the south correspond to the blueshifted lobe ($v_{LSR} = -20.5$ to $-13.5$ km s$^{-1}$). Contour levels for $^{13}$CO are from 0.4 to 3.0 by 0.4 and from 0.2 to 1.4 by 0.2, respectively (in Jy beam$^{-1}$). Contour levels for 222 GHz are from 0.02 to 0.05 by 0.01 (in Jy beam$^{-1}$). The beam size is shown in the lower right corner.
from this gas integrated from $-47$ to $-20$ km s$^{-1}$ and from 0 to 25 km s$^{-1}$. There is no correspondence between this high-velocity $^{13}$CO component and the $^{12}$CO 4–3 bullets detected by Hatchell et al. (1999). The latter are $\sim 10^\circ$ away from the core and have velocities of $-120$ and 60 km s$^{-1}$ LSR (a velocity range not covered by our observations). A position-velocity diagram along the axis of the second outflow detected in $^{12}$CO by Ladd & Hodapp (1997) (P.A. = $-45^\circ$) was also constructed, but no emission was detected.

Images of the C$^{18}$O $J = 1$–0 emission at 109.782182 GHz were also made and show a core surrounded by a poorly imaged halo. There is no evidence of the Cep E outflow, which is not unexpected from this optically thin emission.

6.2. Continuum Emission at 222 and 110 GHz

The right panels of Figure 11 display the continuum emission at 222 and 110 GHz around IRAS 23011 + 6126. The 222 GHz image shows two unresolved sources in a 1.38' x 1.06' beam, with integrated fluxes of 90 and 67 mJy, respectively. At 110 GHz, the continuum emission is resolved and has a diameter of $\sim 3^\prime$ or $\sim 2200$ AU (at 730 pc) and a flux of 35 mJy. It is tempting to interpret these observations as a double source surrounded by an envelope. The presence of a second source strongly suggests that the multiple outflows are due to multiple sources and not to precession. The projected distance between these sources is $\sim 1.4$ or $\sim 1000$ AU at 730 pc. This separation implies a long orbital period, even for an intermediate-mass system, with a range of $7 \times 10^3$–$10^4$ yr, i.e., larger than the kinematical age of the outflow.

Using a dust temperature of 18 K and $\beta \sim 2$ (Ladd & Howe 1997), a gas-to-dust ratio of $\sim 100$, and dust opacities of 0.005 cm$^2$ g$^{-1}$ (Preibisch et al. 1993), the masses associated with the two 222 GHz sources, within 1'4, are 2.5 and 1.8 $M_\odot$. From the 110 GHz continuum, the mass associated with the envelope is found to be 13.6 $M_\odot$. Ladd & Howe (1997), for comparison, computed a mass of 10 $M_\odot$ within a radius of 3000 AU. At 110 GHz, there is no spatial resolution to separate the two sources.

7. IRAS 23011 + 6126 SPECTRAL ENERGY DISTRIBUTION

The CVF ISOCAM observations clearly detect an embedded source that we identified with IRAS 23011 + 6126. Figure 12 shows the composite SED of IRAS 23011 + 6126. It resembles that of a class I source (Lada 1987) rather than a class 0 as proposed by Lefloch et al. (1996), based on millimetric observations. Presently, there are reasons to believe that the distinction between class 0 and class I is not as sharp as previously thought (see, e.g., Gregersen et al. 2000).

Following Noriega-Crespo et al. (1998), model fits to the SED are calculated assuming (1) a dust opacity dominated by bare silicates at a temperature of 18 K and a density of $7.5 \times 10^3$ cm$^{-3}$, and (2) silicates with a thin ice mantle at a temperature of 18 K and a density of $6 \times 10^4$ cm$^{-3}$. The models assume power-law density and temperature distributions, with a core inner radius of 0.065 AU and outer radius of 2500 AU. As Figure 12 shows, the continuum level of ISOCAM observations near log ($v$) $\sim 13.3$ is lower than that of the bare silicates model. As the success of the model using silicates with a thin ice mantle suggests, this can be attributed to absorption by H$_2$O at 10–12 μm. The effect has been noticed in other low-mass protostars such as Elias 29 (Boogert 1999). This model produces a mass envelope of 13.2 $M_\odot$ and bolometric luminosity of $\sim 34 L_\odot$. Comparable masses have been obtained assuming a constant density over a spherical volume (10 $M_\odot$; Ladd & Howe 1997) and in dust temperature-dependent models (18 $M_\odot$; Lefloch et al. 1996). The bolometric luminosity derived by our models, however, is a factor of 2 smaller than these cases, $\sim 30$ versus 70 or 100 $L_\odot$. We suspect that the discrepancy is due to the integration methods used, since coarse approximations overestimate the integrated flux. Our estimates of the luminosity and envelope mass are more appropriate for an intermediate-mass object rather than a low-mass class I system, although not as massive and luminous as IRAS 05553 + 1631 (= GAL 192.16–03.82; Shepherd et al. 1998) or IRAS 20126 + 4104 (Shepherd et al. 2000).

8. CONCLUSIONS

The Cep E outflow has been studied in the mid-IR ($\sim 5–17$ μm) and far-IR ($\sim 40–200$ μm) using the ISO instruments ISOCAM and LWS and at millimetric wavelengths (110.2 and 222 GHz) using OVRO. In the near- and mid-IR, the Cep E morphology is similar to that expected for a jet-driven outflow, where the leading bow shocks entrain and accelerate the surrounding molecular gas (e.g., Raga & Cabrit 1993; Masson & Chernin 1993). As expected, fine-structure atomic/ionic emission lines are found, which very likely come from the leading bow shock, in both the Mach disk and the stagnation tip, where J-shocks are dominant (Fig. 13). The H$_2$, H$_3$, and CO molecular emission could arise farther “downstream” at the bow shock wings where the shocks are oblique and more likely to be C-type (Smith 1991). The range of shock velocities to excite these species is

![Fig. 10.—Position-velocity diagram in the $^{13}$CO $J = 1$–0 transition along the axis of the Cep E outflow. The lowest contour corresponds to a 2σ level.](image-url)
8–35 km s$^{-1}$. The $^{13}$CO emission arises from entrained molecular gas, and, as in other outflows, a compact high-velocity emission is observed, together with an extended low-velocity component that almost coincides spatially with the H$_2$ near-IR emission. The millimetric continuum emission shows two sources. We identify one of them with IRAS 23011 + 6126, and we postulate that it is the driver of the Cep E outflow; the other, also an embedded source, is likely to be driving one of the other outflows observed in the region. Finally, the strong [C II] 158 μm emission must originate from an extended PDR, very likely excited by the nearby Cep OB3 association. Our main conclusions are as follows:

**Fig. 12.** SED of IRAS 23011 + 6126. Data points are taken from Ladd & Howe 1997 (submillimeter; squares), from Noriega-Crespo et al. 1998 (IRAS and ISOCAM; open triangles and upper limit), and from our new OVRO results (filled symbols). The thick solid line represents the CVF spectra extracted at the source position. A model assuming a dust opacity dominated by bare silicates, at a temperature of 18 K and $n = 7.5 \times 10^4$ cm$^{-3}$, is shown in solid line. The dotted line is for silicates with a thin ice mantle at 18 K and $n = 6 \times 10^6$ cm$^{-3}$.

**Fig. 13.** Schematic view of the different emitting regions in the Cep E outflow adopting a jet-driven model.
1. The mid-IR spectra show strong pure rotational H$_2$ lines that coincide spatially with the H$_2$ 1–0 S(1) 2.12 μm emission. Excitation diagrams indicate that this emission is coming from a region at 1000–1300 K, in agreement with the postshock temperatures expected for shock velocities in the range 20–30 km s$^{-1}$, consistent with C-shock diagnostics of H$_2$ line ratios.

2. The far-IR spectrum is rich in H$_2$O and CO lines. The line fluxes can be modeled using an LVG code, assuming that the H$_2$O and CO emission arises from the same region. Two extreme models fit the observations, with temperatures of either 220 or 1200 K (Table 4). The resulting H$_2$O abundances are between 100 and 4000 times greater than the one found in quiescent molecular clouds, confirming once more the presence of high water abundance in the shocked gas associated with young stellar outflows. From comparison with shock models, we conclude that C-shocks with $v_{\text{shock}} \approx 8$–14 km s$^{-1}$ can reproduce the H$_2$O and CO observations.

3. Two strong atomic lines [O i] 63 μm and [C ii] 158 μm are present in the LWS spectra. The ratio of their fluxes is close to 1, indicating a PDR origin. Taking into account the significant contribution to the [O i] line from J-shocks, and comparing with PDR models (Kaufman et al. 1999), we find that two models reproduce the observations, $G_0 = 30$, $n = 60$ cm$^{-3}$ and $G_0 = 6$, $n = 5500$ cm$^{-3}$ ergs s$^{-1}$ cm$^{-2}$, where $G_0$ is the incident FUV flux in units of $1.6 \times 10^{-3}$ ergs s$^{-1}$ cm$^{-2}$. Cep E is relatively close to the Cep OB3 association, which can produce the diffuse FUV field required by these models.

4. The bipolar outflow can be seen in the high-resolution $^{13}$CO image at 110.2 GHz. This emission is bounded by the H$_2$ condensations. Outflow velocities extend from 0 to $-20$ km s$^{-1}$ and are centered on the ambient cloud velocity of $-11$ km s$^{-1}$. There is also evidence for high-velocity gas at 30 and $-40$ km s$^{-1}$ very close to the source. From the $^{13}$CO observations we estimate, for the north and south outflows lobes, respectively, timescales of 4000 and 8000 yr, mass-loss rates of $7 \times 10^{-6}$ and $6 \times 10^{-6}$ L$_{\odot}$ yr$^{-1}$. This confirms that the outflow is very young as the high water abundance seems to indicate.

5. The continuum images at 222 GHz show the presence of two unresolved sources within the positional error bars of IRAS 23011 + 6126. The masses associated with them are 2.5 and 1.8 M$_{\odot}$. The lower spatial resolution of the continuum observations at 110 GHz allows us to detect the surrounding envelope, which has a mass of 13.6 M$_{\odot}$ and a radius of 1100 AU. No evidence is found for any of the other outflows observed at near-IR or radio wavelengths. The presence of a second source, however, strongly suggests that the multiple outflows are due to multiple sources and not to precession. The separation of these sources is about 1.4' or $\sim 1000$ AU, and so even for an intermediate-mass system, the binary period would be of the order of $7 \times 10^{6}$–$10^{7}$ yr, which is longer than the kinematical age of the outflow.

6. A simple envelope model for the SED of IRAS 23011 + 6126 predicts a mass envelope of 13.2 M$_{\odot}$ and a luminosity of $\sim 30 L_{\odot}$ from silicates with thin ice mantles. The spectral features observed at 5–17μm in IRAS 23011 + 6126 are closer to those of a class I source, and the mass and luminosity estimated are those of an intermediate-mass YSO, rather than a low-mass class 0 object.

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