DETECTION OF THE 62 \( \mu m \) CRYSTALLINE \( \text{H}_2\text{O} \) ICE FEATURE IN EMISSION TOWARD HH 7 WITH ISO-LWS

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ABSTRACT

We report the detection of the 62 \( \mu m \) feature of crystalline water ice in emission towards the bowshaped Herbig-Haro object HH 7. Significant amounts of far infrared continuum emission are also detected between 10 and 200 \( \mu m \), so that Herbig-Haro objects cease to be pure emission-line objects at FIR wavelengths. The formation of crystalline water ice mantles requires grain temperatures \( T_g \gg 100 \text{ K} \) at the time of mantle formation, suggesting that we are seeing material processed by the HH 7 shock front. The deduced ice mass is \( \sim 2 \times 10^{-5} \text{ M}_\odot \), corresponding to a water column density \( N(\text{H}_2\text{O}) \sim 10^{18} \text{ cm}^{-2} \); an estimate of the \([\text{H}_2\text{O}]/[\text{H}] \) abundance yields values close to the interstellar gas-phase oxygen abundance. The relatively high dust temperature and the copious amounts of gas-phase water needed to produce the observed quantity of crystalline water ice, suggest a scenario where both dissociative and non-dissociative shocks co-exist. The timescale for ice mantle formation is of the order of \( \sim 400 \text{ years} \), so that the importance of gas-phase water cooling as a shock diagnostic may be greatly diminished.

Subject headings: (ISM:) dust, extinction — ISM: Herbig-Haro objects — ISM: individual (HH 7) — ISM: lines and bands — infrared: ISM: continuum — infrared: lines and bands — infrared: individual objects (HH 7) — infrared: lines and bands — infrared: lines and bands — infrared: lines and bands — infrared: lines and bands

1. INTRODUCTION

Herbig-Haro objects (HH; Haro 1950, Herbig 1951) are emission-line objects acting as signposts for the shock regions (Draine, Roberge & Dalgarno 1983; Hollenbach & McKee 1989) originating at the interface between stellar winds accelerated by Young Stellar Objects (YSOs) and the circumstellar or cloud ambient material. The temperature of dust grains in these shock regions can raise to only a few hundred degrees at most in dissociative shocks (Hollenbach & McKee 1989), so that their thermal emission cannot be detected below 10 \( \mu m \).

The instruments on board the Infrared Space Observatory satellite (ISO, Kessler et al. 1996) opened unprecedented possibilities for far infrared continuum studies of cold objects, including HH objects. In this Letter we present the data obtained with the Long (LWS, Clegg et al. 1995) and Short (SWS, de Graauw et al. 1996) Wavelength Spectrometer towards HH 7, the leading bowshaped shock of the HH 7-11 chain emanating from the YSO SVS 13, in the star forming region NGC 1333 in Perseus (d=350 pc). Details about the observations and data reduction are given elsewhere (Molinari et al. 1999). In Sect. 2 the additional data analysis procedures we adopted to derive a reliable continuum spectrum for HH 7 are discussed. Nomenclature for the ten LWS detectors is described in the ISO Data User Manual [http://www.iso.vilspa.esa.es/manuals/lws_idum]. Detectors SW1 to SW5 (43-90 \( \mu m \)), and LW1 to LW5 (80-197 \( \mu m \)), are sometimes referred to as “short” and “long” wavelength detectors respectively.

2. RESULTS

The LWS beam centered on HH 7, also includes object HH 8 somewhat 20” off-axis and HH 10 at the edge of the beam; these objects are however fainter than HH 7 at 2 \( \mu m \) (Molinari et al. 1999), and the beam profile suppresses their possible contribution even more. Apart from a contamination by the strong nearby source SVS 13, which will be discussed in detail in Sect. 2.2 it is plausible to assume that HH 7 dominates the observed spectrum.

2.1. The 62 \( \mu m \) feature

In Fig. 2.1 the complete spectra observed towards HH 7 and SVS 13 are shown. A broad feature extending from roughly 50 to 70 \( \mu m \) is clearly visible in the HH 7 spectrum. For clarity the SW3 detector spectrum, with an offset applied to align it with the continuum of the adjacent detectors, is shown with plus symbols. The pri-
mary concern was to make sure that the 50-70 \( \mu m \) feature was not a result of a residual instrumental effect and that it is intrinsic to HH7. The passband calibration is known to be somewhat inaccurate for detector SW1 (it may be worse than 50% both in absolute and relative terms) which is the most sensitive to transients. Detectors SW2, SW3 and SW4 however, are stable in relative (passband) terms and a conservative figure of 30% can be assumed for their absolute calibration accuracy. The possibility that the broad feature visible on Fig. 2.1 may be due to the near-IR leaks present in the LWS detectors filters [http://isowww.estec.esa.nl/notes/lws_0197.htm](http://isowww.estec.esa.nl/notes/lws_0197.htm) can also be excluded. Finally, this feature might result from contamination effects from the bright nearby source SVS 13, which is the candidate exciting source for HH7; these effects will be discussed in detail in the Sect. 2.2.

**Fig. 1** – LWS averaged spectra observed towards HH7 (bottom) and SVS 13 (top). The different portions are the 10 LWS detectors, labeled with the names used in the text. The plus symbols for HH 7 represent detector SW3 with an applied offset of 5 Jy to bring it in line with the adjacent detectors.

Here we just note here that if the 50-70 \( \mu m \) feature seen on the HH 7 spectrum was due to a fraction of the flux emitted by the nearby contaminating source SVS 13, we would expect to see the same feature at a comparable “line-to-continuum” ratio on the SVS 13 continuum spectrum; Fig. 2.1 clearly shows that this is not the case. We conclude that the 50-70 \( \mu m \) feature is real and intrinsic to HH7 and we consider it as a 2\( \sigma \) detection, assuming that the noise of the feature is equal to half the gap between detectors SW3 and SW2. We identify this as the 62 \( \mu m \) feature due to the longitudinal acoustic modes of crystalline water ice (Bertie, Labbe & Whalley [1996]), observed for the first time by Omont et al. [1990] in the expanding envelopes of post-AGB stars; ISO-LWS has detected this feature in the spectra of similar objects (Barlow [1998] and of a few Herbig Ae/Be stars (Waters & Waelkens [1998]; Malfait et al. [1999]). It is the first time this feature has been detected towards Herbig-Haro objects.

### 2.2. The 2-200 \( \mu m \) Continuum

Several SWS line scans were used to estimate the continuum at different wavelengths for \( \lambda < 40 \mu m \). The line-free portions of each individual spectrum were used to build flux histograms, and a gaussian was then fitted to the core of the distribution to obtain the centroid (average flux) and the standard deviation; the latter was then divided by the square root of the number of points in histogram to get an estimate of the uncertainty. These uncertainties reflect the internal accuracy of the estimates; in fact the true uncertainty may be higher. In particular, all data shortward of \( \approx 10 \mu m \) are at the detection limit of the SWS and they will be treated as 1\( \sigma \) upper limits.

LWS scans were averaged using the ISO Spectral Analysis Package (ISAP [http://www.ipac.caltech.edu/iso/isa/](http://www.ipac.caltech.edu/iso/isa/)) routine INSPECT.RASTER to determine the relative position of HH7 and SVS13 in the \([Y,Z]\) spacecraft frame of reference. For each Mars raster position along the direction connecting the two sources, we averaged the Mars spectra detector by detector; each detector average at the various off-axis positions was then ratioed to the analogue detector average of the on-axis spectra, and a set of ten contamination factors for each position was obtained. A spline interpolation was then used to estimate these factors (one per detector) at an off-axis distance of 68". The distance between HH7 and SVS13: we find values 0.024, 0.025, 0.037, 0.05, 0.075, 0.09, 0.10, 0.11, 0.13 and 0.15, which increase with wavelength as expected due to diffraction. We multiplied the observed SVS13 spectra by these numbers, and the resultant spectrum was subtracted from the observed HH7 spectrum.

This method for estimating the contamination from nearby sources inevitably suffers from the irregular sampling of the Mars raster map. Raster points did not lay exactly along the HH7-SVS13 direction on the focal plane, and the interpolation between the correction factors estimated at each relevant raster position introduced an additional uncertainty. At the end of the procedure (see Fig. 3) we find worse alignment between adjacent LW detectors, and detector SW5 goes to negative flux values (not reported on Fig. 3). We believe this may be due to the fact that as the magnitude of the applied contamination correction increases with wavelength, so does the associated uncertainty; in particular, detector SW5 is in the critical region where the contamination correction starts to be high (2-3 times higher than for SW2 and SW4) while the observed signal is still low (similar to SW2), so that a slightly overestimate of the contamination fraction is enough to bring its corrected values below zero. The LWS LW detectors are those for which the contamination fractions are higher and for which diffraction and source’s extension effects (which here have been neglected) are more severe. An additional complication, which does not affect the SW detectors, is that heavy fringing is observed (which has been here removed using standard tools available in ISAP); this has the effect of modulating the
beam size as a function of wavelength even within individual detector bands. We did not take this into account, instead deriving a single contamination factor per detector; multiplying or dividing by a constant, however, has the effect of changing the slope. Hence, although the observed continuum levels are high enough to ensure that an important part of the observed signal can confidently be assigned to HH7, the exact absolute fluxes and spectral shape in this wavelength range remain highly uncertain.

On the short wavelength side of the LWS spectrum on the other hand, the existence of intrinsic continuum emission from HH7 depends more critically on the particular value of the contamination factors; doubling this factors would lower the spectrum to negative flux levels. If, however, the λ < 80 µm flux observed towards HH7 were due to contamination, we would expect to see the 62 µm emission feature also on the continuum spectrum of SVS13 and with a comparable “line/continuum”; instead, no trace of such a feature is seen on the SVS13 continuum (see Fig. 2.1). We conclude that FIR emission which is intrinsic to HH7 has been detected, showing for the first time that Herbig-Haro objects cease to be exclusively emission-line objects at FIR wavelengths.

3. DISCUSSION

In the following discussion we will assume that the FIR and mm continuum arise from the same region of space, based on the spatial coincidence between the HH objects and the mm emission distribution; currently available 50-100 µm data on the region (Harvey et al. 1984, 1998; Jenkins et al. 1987), however, do not have enough spatial resolution or sensitivity to support this claim.

The spectral energy distribution (SED) from HH7 will be modeled as thermal emission from dust grains composed of a silicate core and a water ice mantle. Absorptivities between 2 and 300 µm were computed with Mie theory in the formulation of Wickramasinghe (1967), using the complex refractive indices for crystalline water ice (Bertie et al. 1996) and silicate (Draine 1985). Longward of 300 µm the silicate absorptivities by Draine (1985) were adopted; inclusion of water ice mantles may steepen the slope of the Q_{abs} vs λ relationship (Aannestad 1977), possibly leading to underestimation of the dust mass. Radiative transfer is approximated with an analytical treatment where dust is distributed on a sphere which is characterised by radial density and temperature gradients (Noriega-Crespo, Garnavich & Molinari 1998). The presence of a cold dust clump centered on the location of HH7 and extending over a larger area than the one traced by the optical or near-IR emission (LeFloch et al. 1998), justifies a treatment where a dust clump is centrally heated by the HH7 shock. Fig. 2 presents the complete SED towards HH7, after removal of the contamination from SVS13 (see Sect. 2.2). The LWS detectors SW1 to SW4 have been rescaled to a common level preserving their original mean value.

The fit plotted in Fig. 2 is obtained adopting a dust clump radius of 0.06 pc, which approximates the radius of the average LWS beam size at a distance of 350 pc, and the size of the 1.25 mm continuum emission area (LeFloch et al. 1998). The density is assumed constant and equal to 6×10^{−7} cm^{-3} while the temperature varies from ~10 to 200 K with a ~ −0.4 power-law radial gradient. The
bolometric luminosity obtained integrating the model fit is $L_{fit} = 3.7 \ L_\odot$, while integration of the contamination-corrected SED (Sect. 2.2) yields $L_{sed} \lesssim 4.5 \ L_\odot$ (since $\lambda < 10 \ \mu m$ and $\lambda = 1.25 \ mm$ data are to be considered upper limits): this is about a factor 30 higher than the cooling via atomic and molecular lines observed towards HH 7 (Molinari et al. 1999). The fitted model predicts that the bulk of the 62 $\mu m$ feature is emitted by dust at temperatures $T \gtrsim 30 \ K$ concentrated inside a 4$''$-radius region centered on HH 7, a size comparable to that of the optical and near-IR emission which traces the shock front. Since these grains should have experienced a rise in temperature to values $\gtrsim 100 \ K$ in order for ice mantles to be in crystalline state, it is plausible that the 62 $\mu m$ feature originates from dust which has been processed by the HH 7 shock. The dust mass in the 4$''$-radius region centered on HH 7 amounts to $5 \times 10^{-5} \ M_\odot$ (the total dust mass implied by the model fit is $\sim 0.035 \ M_\odot$); the relative proportion of core and mantle (the core has 70% of the total grain radius) implies a water ice mass of $2 \times 10^{-5} \ M_\odot$, or a H$_2$O column density $\sim 1.1 \times 10^{18} \ cm^{-2}$. H$_2$ pure rotational lines (Molinari et al. 1999) suggest N(H$_2$) $\sim 4.4 \times 10^{20} \ cm^{-2}$ in the same 4$''$-radius region, implying [H$_2$O]/[H$_2$] $\sim 1.25 \times 10^{-3}$, or a factor $\sim 4$ higher than the interstellar O gas-phase abundance (Meyer et al. 1998). However, this number should be regarded as an upper limit because our model assumes that all dust grains are coated with ice mantles, which is not necessarily true; besides, we cannot exclude the presence of cold H$_2$ (T $\lesssim 100 \ K$) which our ISO observations (Molinari et al. 1999) would not trace. This water abundance, even if considered only as an order-of-magnitude estimate, is however much higher than the gas phase water abundance ([H$_2$O]/[H$_2$] $\lesssim 10^{-5}$) deduced from FIR lines (Molinari et al. 1999), and it would essentially imply that most of the oxygen is locked into water ice.

Due to the uncertainty about the 45 $\mu m$ feature (see above), it hard to tell from the observational viewpoint whether gas-phase water produced behind the HH 7 shock front (Kaufman & Neufeld 1994) is deposited onto bare warm grains, or pre-existing ice mantles are warmed-up during the passage of a relatively gentle shock front. The ice optical constants that we used (Bertie et al. 1969) are from laboratory samples obtained by direct deposition at T=173 K and subsequent cooling to 100 K; hence the good simultaneous fit of the 62 and 45$\mu m$ features would tend to support the first scenario. The physical condition behind low velocity ($v_s \lesssim 40 \ km \ s^{-1}$), non-dissociative, shocks are favourable for the rapid gas-phase incorpora-

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