IRAS 23385+6053: A PROTOTYPE MASSIVE CLASS 0 OBJECT
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ABSTRACT
IRAS 23385+6053 is a young stellar object with a luminosity of $\sim 1.6 \times 10^4 L_\odot$ at a kinematic distance of 4.9 kpc. This candidate precursor of an ultracompact H II region is associated with a millimeter source detected at the James Clerk Maxwell Telescope but is undetected at centimeter wavelengths with the VLA. We observed this source with the Owens Valley Radio Observatory millimeter array at 3.4 mm in the continuum, HCO$^+$ (1 $\to$ 0), H$^{13}$CO$^+$ (1 $\to$ 0), and SiO ($v = 0, 2 \to 1$) line emission and with CAM aboard the Infrared Space Observatory at 6.75 and 15 $\mu$m. The IRAS source is coincident with a 3.4 mm compact ($r_{\text{core}} = 0.048$ pc) and massive ($M = 370 M_\odot$) core, which is undetected at 15 $\mu$m to a 3 $\sigma$ level of 6 mJy; this is compatible with the derived H$_2$ column density of $\sim 2 \times 10^{24}$ cm$^{-2}$ and the estimated visual extinction $A_v \sim 2000$ mag. We find $L_{\text{submm}}/L_{\text{bol}} \sim 3 \times 10^{-3}$ and $M_{\text{vir}}/M_\odot \gg 1$, which is typical of class 0 objects. The source is also associated with a compact outflow characterized by a size $\lesssim r_{\text{core}}$, a dynamical timescale of $\lesssim 7 \times 10^3$ yr, and a mass-loss rate $M \gtrsim 10^{-3} M_\odot$ yr$^{-1}$. The axis of the outflow is oriented nearly perpendicular to the plane of the sky, ruling out the possibility that the nondetection at 15 $\mu$m is the result of a geometric effect. All these properties suggest that IRAS 23385+6053 is the first example of a bona fide massive class 0 object.

Subject headings: infrared: ISM: continuum — ISM: individual (IRAS 23385+6053) — ISM: jets and outflows — ISM: molecules — radio continuum: ISM — radio lines: ISM — stars: formation

1. INTRODUCTION
The last few years have seen a rapid growth in observations aimed at identifying intermediate- and high-mass star-forming sites in a wide range of evolutionary stages ranging from “hot cores” (Cesaroni et al. 1994) to ultracompact H II (UCH II) regions (Wood & Churchwell 1989) to proto-Ae/Be stars (Hunter et al. 1998). The characterization of the earliest stages of high-mass star formation is more difficult than for low-mass objects, given their shorter evolutionary timescales. The likely candidates must be luminous, embedded in dense circumstellar environments, and not associated with H II regions (cf. Habing & Israel 1979).

We have undertaken a systematic study to identify a sample of massive protostellar candidates, selecting sources from the IRAS-PSC2 catalog and filtering them according to the above criteria. On the basis of an H$_2$O maser (Palla et al. 1991), ammonia lines (Molinari et al. 1996), and centimeter and submillimeter continuum observations (Molinari et al. 1998a, 1998b), we were finally left with about a dozen candidates that may be precursors of UCH II regions. Several of these sources have been observed recently with the IRAM 30 m telescope (Brand et al. 1998) and some with the Infrared Space Observatory (ISO), in order to characterize these sources over a wide range of wavelengths. We are now beginning a program of high spatial resolution millimeter-wave observations of these objects. This Letter presents the results for the first source imaged, IRAS 23385+6053, at a kinematic distance$^6$ of 4.9 kpc (using the Brand & Blitz 1993 Galactic rotation curve). According to the definition (see, e.g., André 1996), this is an excellent candidate for a high-mass counterpart to class 0 objects. It is associated with an H$_2$O maser and with NH$_3$ line and submillimeter continuum emission, while no centimeter continuum emission was detected in our VLA observations down to a level of $\sim 0.5$ mJy beam$^{-1}$.

2. OBSERVATIONS
The field centered on IRAS 23385+6053 was observed at 88 GHz (continuum and lines) with the Owens Valley Radio Observatory (OVRO) millimeter-wave array during 1998 January–February. Two configurations of the six 10.4 m telescope antennas provided baselines in the range 15–240 m. Cryogenically cooled SIS receivers have typical average system temperature of $\sim 350$ K. The continuum observations used two 1 GHz wide bands of an analog correlator. For the line observations, the digital correlator was split into several bands, enabling simultaneous observations of the HCO$^+$ (1 $\to$ 0) and H$^{13}$CO$^+$ (1 $\to$ 0) rotational lines with an $\sim 20$ km s$^{-1}$ bandwidth and a $0.84$ km s$^{-1}$ resolution; the HCO$^+$ (1 $\to$ 0) line was also observed with an $\sim 80$ km s$^{-1}$ bandwidth and a $3.4$ km s$^{-1}$ resolution. Additionally, data on the SiO ($v = 0, 2 \to 1$) line were acquired in the image sideband of the HCO$^+$ (1 $\to$ 0) line with the same bandwidths and resolutions. Gain and phase were calibrated by means of frequent observations of the quasar 0224+671; 3C 273 was used for the passband calibration. The flux density scale was determined by observations of planets, and the estimated uncertainty is less than 20%. The synthesized beam size is $4.1 \times 3.5$. Noise levels in the maps are $\lesssim 0.7$ mJy beam$^{-1}$ for the continuum, and $\sim 20$ and $\sim 45$ mJy beam$^{-1}$

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$^6$ In Molinari et al. (1996), we quoted a distance of 6.9 kpc derived from the observed Galactic velocity field, which, however, should not be used for $d \geq 5$ kpc in the second and third quadrants.
channel$^{-1}$ for the low- and high-resolution spectral data, respectively.

ISO (Kessler et al. 1996) observations with CAM (Cesarsky et al. 1996) were made in the staring mode on 1997 June 18. Diffraction-limited images (resolution 2″2 and 5″, respectively) were obtained in the two broadband filters LW2 ($\lambda_{\text{eff}} = 6.75$ μm, $\Delta\lambda = 3.5$ μm) and LW3 ($\lambda_{\text{eff}} = 15.0$ μm, $\Delta\lambda = 6$ μm). The pixel field of view is 3″, and the absolute pointing accuracy of the satellite was presumably within 3″ at the time of the observations. More than 50 frames per filter were obtained with a 2 s integration time per frame, and the expected 3 $\sigma$ sensitivity limits were 0.33 and 0.45 mJy arcsec$^{-2}$ in LW2 and LW3, respectively. The data have been reduced using the CAM Interactive Analysis (V2.0), and the absolute calibration is accurate to within 20%.

3. RESULTS

The left panel of Figure 1 shows the contour plot of the HCO$^+$ (1 $\rightarrow$ 0) integrated line intensity overlaid on the CAM-LW3 filter 15 μm image. The right panel of Figure 1 shows an enlargement of the central region, with a contour plot of the 3.4 mm continuum. With the exception of HCO$^+$ (1 $\rightarrow$ 0) emission in one area to the northeast, the HCO$^+$ line and the 3.4 mm continuum arise from the central region where the 15 μm continuum is faintest; HCO$^+$ also shows an extension toward the south-southeast.

In the dark region at the center of the 15 μm image, flux densities on the order of $\sim$1 mJy arcsec$^{-2}$ are found. Similar values are also found in the southern portion of the CAM field, suggesting that such a constant level is due to faint foreground diffuse emission. The rms noise computed in the southern 20″ of the image is $\sim$0.15 mJy arcsec$^{-2}$. Similar flux densities and rms levels are obtained for the 6.75 μm image. We thus conclude that no 15 μm source is detected at the position of the central 3.4 mm continuum peak down to a 3 $\sigma$ level of $\sim$0.45 mJy arcsec$^{-2}$, which, when integrated over the deconvolved area of the 3.4 mm core, corresponds to $\sim$6 mJy.

The 3.4 mm continuum core is compact, with slight elongations to the southeast and to the north (Fig. 1). The total integrated flux density is 19 mJy, and the deconvolved source size is 4″5 $\times$ 3″6, corresponding to an average radius of 0.048 pc at a distance of 4.9 kpc. The continuum emission peaks at $\alpha(1950) = 23^\circ38^\prime31^\prime\prime.4, \delta(1950) = +60^\circ53'50''$ and is probably due solely to dust thermal emission, since the extrapolation at 3.4 mm of the 2 cm upper limit with an ionized wind model $\sim\nu^{-8}$ (Panagia & Felli 1975) yields less than 10% of the observed flux density.

Figure 2 shows the complete spectral energy distribution (SED) of IRAS 23385+6053. The OVRO flux density is consistent with those from the James Clerk Maxwell Telescope (JCMT) (Molinari et al. 1998a), indicating that no significant diffuse millimeter emission has been missed by the interferometer. On the other hand, the IRAS flux densities include contributions from all the sources seen in the 15 μm image of Figure 1. Indeed, the IRAS 12 and 25 μm points in Figure 2 (5.05 and 17.8 Jy, respectively) are compatible with the CAM 6.75 and 15 μm flux integrated over all the bright emission.

Fig. 1.—Left panel: CAM LW3 filter (15 μm) image of IRAS 23385+6053, with the contour plot of the HCO$^+$ (1 $\rightarrow$ 0) line intensity integrated over a velocity interval of $\sim$7 km s$^{-1}$ centered at $V_{\text{LSR}} = -51.0$ km s$^{-1}$ superposed; the CAM image has been resampled at the same pixel size used to reconstruct the OVRO maps. To avoid saturation at the peak emission, contours are spaced by 0.15 from 0.3 to 1.5, by 0.3 from 1.5 to 3.0, and by 0.5 from 3.5 to 5.6 Jy km s$^{-1}$ beam$^{-1}$. The dashed circle shows the OVRO primary beam HPBW. Right panel: enlargement of the previous image around the central position with the contour plot of the OVRO 3.4 mm continuum emission from 2.0 to 9.0 by 0.7 mJy beam$^{-1}$ superposed. The circle shows the JCMT 19" aperture centered at the 1.1 mm peak position. The gray ellipse is the OVRO synthesized beam FWHP.

Fig. 2.—SED of the IRAS 23385+6053 core. The dotted line shows the model fit described in the text.
visible on the CAM image (∼4.8 and 9.3 Jy, respectively, in an area of $6.8 \times 10^{-2}$ sr), while they lie more than 3 orders of magnitude above the CAM flux density limits for the core estimated above. Clearly, the 6.75 and 15 μm emission area, which is not directly related to the millimeter core, is responsible for the IRAS 12 and 25 μm flux densities; however, it is unlikely that it contributes a significant fraction of the 60 and 100 μm IRAS flux densities because (1) at millimeter wavelengths, the core is compact, and no discrete or diffuse continuum emission is detected at either the OVRO or the JCMT, and (2) a power-law extrapolation of the 6.75, 12, 15, and 25 μm flux densities to longer wavelengths leads to flux densities at 60 and 100 μm, which are ≤10% of the observed values. We conclude that the millimeter core is the only source contributing significantly at 60 and 100 μm.

In Figure 2, the dotted line is a fit to the data, which was obtained by adopting a spherical envelope model where density and temperature vary according to radial power laws with exponents −0.5 and −0.4, respectively. The density and temperature at the external radius, which is the observed $r_{core} = 0.048$ pc, are $7 \times 10^{8}$ cm$^{-3}$ and 40 K, respectively. The opacity is $k_\nu (\text{cm}^2 \text{g}^{-1}) = \kappa_{230} [\nu (\text{GHz})/230.6]^{1.9}$, where $\kappa_{230} = 0.005$ cm$^2$ g$^{-1}$ (Preibisch et al. 1993). We compute the bolometric luminosity of the source by integrating the data with a power-law interpolation scheme, excluding the IRAS 12 and 25 μm flux densities and using the CAM upper limit at 15 μm. At the adopted distance of 4.9 kpc, we find $L_{bol} = 1.6 \times 10^{4} L_{\odot}$. Integrating the fitted density power law and adopting a gas-to-dust ratio of 100 by mass, we estimate a mass of $\sim 370 M_{\odot}$ and a mean H$_2$ column density of $\sim 2 \times 10^{24}$ cm$^{-2}$ for the core (corresponding to a visual extinction $A_V \sim 2000$). We also computed the mass of the core from HCO$^+$ line emission. The optical depth in each channel within 3 km s$^{-1}$ of $V_{LSR} = -51$ km s$^{-1}$ was estimated from the HCO$^+$/H$^13$CO$^+$ ratio, assuming a $^{12}$C/$^{13}$C = 87 abundance ratio by using the Galactic abundance gradient and the local interstellar medium value given in Wilson & Rood (1994) and a source Galactocentric distance of $\sim 11$ kpc; we find that the core of the main isotope line is optically thick. We derive a lower limit (due to the optical depth) for the H$_2$ mass of 180 $M_{\odot}$ by assuming $T_{\text{ex}} = 30$ K, based on the peak HCO$^+ (1 \to 0)$ synthesized beam brightness temperature, and [HCO$^+$/H$_2$] = $10^{-9}$. This value compares reasonably well with a virial mass of 160 $M_{\odot}$ obtained from the line width (∼3.5 km s$^{-1}$) and HCO$^+ (1 \to 0)$ core radius (∼0.06 pc).

In Figure 3, we present profiles of the SiO ($v = 0$, $2 \to 1$) and HCO$^+ (1 \to 0)$ lines at low spectral resolution and the HCO$^+ (1 \to 0)$ and H$^13$CO$^+$ (1 $\to$ 0) lines at higher resolution, integrated over the $\sim 20$ arcsec$^2$ region centered on the core peak. Both the SiO and HCO$^+$ profiles show broad wings, while no wing emission is detected from H$^13$CO$^+$ (1 $\to$ 0). Images of the HCO$^+$ and SiO emission integrated over the blue (from $-63$ to $-53$ km s$^{-1}$) and the red (from $-47$ to $-37$ km s$^{-1}$) wings are shown in Figure 4. A compact outflow centered on the continuum source is detected; both the blue and red lobes are visible in SiO ($v = 0$, $2 \to 1$), whereas only the blue lobe is clearly detected in HCO$^+ (1 \to 0)$, although a faint red lobe may be present. The lobes are barely resolved; their position relative to each other (i.e., their degree of overlap) suggests that the inclination of the outflow axis can be no more than 30° with respect to the line of sight (Cabrit & Bertout 1986, 1990). This orientation of the outflow rules out any possibility that the large extinction derived toward IRAS 23385+6053 and the nondetection at 15 μm may result from geometrical effects (e.g., an edge-on disk). Properties of the IRAS 23385+6053 outflow are listed in Table 1. Column density, mass, momentum, and energy are computed in each velocity channel and finally summed, while the dynamical timescale is averaged over the velocity channels. We estimated the column density of material by assuming LTE and optically thin approximations in all the line wing channels within the velocity ranges previously listed and by assuming the above-determined

![Fig. 3. OVRO spectra integrated over an ∼20 arcsec$^2$ area centered on the core. Top panel: low resolution; rms = 0.02 Jy. Bottom panel: high resolution; rms = 0.04 Jy. In all panels, the vertical scale is the flux density in units of Jy.](image)

![Fig. 4. Outflow maps of IRAS 23385+6053. The contour levels start at 0.3 and increase by 0.12 Jy km s$^{-1}$ for the two maps; the dotted contour corresponds to ∼0.3 Jy km s$^{-1}$. The cross represents the position of the peak in the 3.4 mm continuum map. The full ellipse is the OVRO beam.](image)
excitation temperature of 30 K for both HCO\(^+\) and SiO. For both molecules, we adopt an abundance fraction of \(10^{-9}\) relative to H\(_2\). The velocity measured in the lobes is a good estimate of the true gas velocity because the outflow axis is nearly perpendicular to the plane of the sky. This configuration prevents an accurate measure of lobe size, but a reasonable estimate can be made based on the nondetection at 15 \(\mu\)m. Since any outflow more extended than the core would have created a cavity through which mid-infrared radiation could have escaped, we infer that the extent of the flow lobes is less than the core size. The size of the lobes and the dynamical timescale of the outflow are therefore upper limits, while the mass-loss rate and kinetic luminosity are lower limits.

The flow mechanical power and mass-loss rate in Table 1 are high compared with the values characterizing outflows powered by low-mass protostars (see, e.g., Fukui et al. 1993), but they are in good agreement with those for high-mass young stellar objects (Shepherd & Churchwell 1996). Nevertheless, the dynamical timescale is similar to values found for the youngest outflows around low-mass class 0 objects (André, Ward-Thompson, & Barsony 1993).

4. IRAS 23385+6053: A MASSIVE CLASS 0 OBJECT

IRAS 23385+6053 was not detected at 6 and 2 cm with the VLA B array with 3 \(\sigma\) sensitivity limits of \(\sim 0.5\) and \(\sim 0.8\) mJy beam\(^{-1}\), respectively (Molinari et al. 1998b), implying that any associated H\(_2\) region, if present, must be optically thick and very compact. In this latter case, from the VLA synthesized beam size and assuming that the source has not been detected because of beam dilution, the 2 cm upper limit leads to an upper limit for the radius of an optically thick, spherical, and homogeneous H\(_2\) region of \(r_{\text{H}2} \lesssim 100\) AU (see also Molinari et al. 1998b). An H\(_2\) region originating from a B0 zero-age main-sequence (ZAMS) star (which has a luminosity comparable to the bolometric luminosity of IRAS 23385+6053) in a dense (\(n_{\text{H}2} \sim 10^7\) cm\(^{-3}\)) environment takes only a few years to expand to a radius of 100 AU (De Pree, Rodríguez, & Goss 1995). However, a modest accretion rate of \(4 \times 10^{-7} M_\odot\) yr\(^{-1}\) could squelch the expanding H\(_2\) region (see, e.g., Walmsley 1995), thus explaining the properties of our source in terms of a heavily obscured B0 ZAMS with a residual accretion. Another possible explanation is that there is no H\(_2\) region because IRAS 23385+6053 has not yet reached the ZAMS. In this case, we assume that the observed bolometric luminosity is due to accretion onto a protostellar core with a bolometric luminosity expressed as \(L_{\text{acc}} = 3.14 \times 10^4 L_\odot (M_*/M_\odot)^{(R_*/R_\odot)} (M/10^{-3} M_\odot\text{ yr}^{-1})\). Since \(L_{\text{acc}}\) is known, we can combine it with the mass-radius relation of Stahler, Palla, & Salpeter (1986), \(R_\odot = 27.2 \times (M_*/M_\odot)^{0.27} (M/10^{-3} M_\odot\text{ yr}^{-1})^{1/3}\), to derive the protostellar mass \(M_*\) as a function of the accretion rate. For an accretion rate of \(M \sim 10^{-3} M_\odot\text{ yr}^{-1}\), which is expected if the outflow (see Table 1) is driven by infall (see, e.g., Shu et al. 1988), we obtain \(M_* = 39 M_\odot\), implying that the embedded IRAS source is a massive protostar. In either case, this source is evidently massive and extremely young.

Based on the evidence presented here, we propose IRAS 23385+6053 as a prototype high-mass class 0 object: it is undetected in the mid-IR (\(\lambda < 15\) \(\mu\)m) and in the radio continuum; it has \(L_{\text{sub/mm}}/L_{\text{bol}} \approx 5 \times 10^{-3}\) (where \(L_{\text{sub/mm}}\) is obtained by integrating longward of 350 \(\mu\)m); and it has a ratio of the envelope to stellar mass greater than 1 (see André et al. 1993), \(M_{\text{env}}/M_* \approx 10\). The very short dynamical timescale (\(\approx 7000\) yr) of the associated compact molecular outflow is also compatible with values found for outflows around low-mass class 0 objects.

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