Astron. Astrophys. 345, L43–L46 (1999)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

A double system of ionized jets in IRAS 20126+4104

P. Hofner[1,2], **R. Cesaroni**[3], **L.F. Rodríguez**[4], **and J. Martí**[5]

[1] Physics Department, University of Puerto Rico at Rio Piedras, P.O. Box 23343, San Juan, Puerto Rico 00931
[2] Arecibo Observatory, NAIC/Cornell University, HC3 Box 53995, Arecibo, Puerto Rico 00612
[3] Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Florence, Italy
[4] Instituto de Astronomia, UNAM, Apdo. Postal 70–264, 04510 México D.F., México
[5] Departamento de Física, Escuela Politécnica Superior, Universidad de Jaén, Calle Virgen de la Cabeza, 2, E-23071 Jaén, Spain

Received 2 March 1999 / Accepted 6 April 1999

Abstract. We have imaged the $7\,$mm and $3.6\,$cm continuum emission from the high mass (proto)star system IRAS 20126+4104 with the VLA. The 7 mm emission appears unresolved with a synthesized beam of $1\farcs7 \times 1\farcs0$, and comparison with 3 mm and $1.3\,$mm fluxes indicates a spectral index of about 3, so that emission from dust with an absorption coefficient proportional to ν is suggested.

The $3.6\,$cm emission consists of two elongated structures of approximate size $0\farcs8\times \leq 0\farcs2$, the northern source being coincident with the millimeter emission. The position angle of both sources is identical to the large scale molecular outflow seen in HCO^+(1–0).

We discuss explanations for the origin of the $3.6\,$cm continuum emission and although a cluster of three ultracompact HII regions provides a feasible model, we favor the interpretation of thermal ionized jets, based on the morphology of the emission, the velocity distribution of water masers coincident with the northern source, and the CH_3CN emission which is oriented perpendicular to the $3.6\,$cm continuum emission. In this case the measured fluxes are consistent with ionization caused by either shocks or stellar UV photons.

Key words: stars: formation – ISM: H II regions – ISM: jets and outflows

1. Introduction

Energetic outflow phenomena such as bipolar molecular flows, Herbig-Haro objects, and emission from shocked H_2 are commonly observed in regions of star formation. Many of these phenomena can be explained by a scenario involving an accretion disk/jet system. For low mass systems there are several excellent observational examples (e.g. Rodríguez et al. 1999, Torrelles et al. 1997) for disk/jet systems, where the disk can be traced by emission from the dust continuum at mm wavelengths, and the jets through their continuum emission at cm wavelengths, which in most cases is thermal emission from ionized gas in the jet. However, for regions where OB type stars are being formed, our knowledge of how the high velocity gas observed in these regions is collimated and driven remains scarce.

In this paper we present observations of the high-mass (proto)star IRAS 20126+4104 (hereafter I20126). This system shows a large bipolar molecular flow and, on a much smaller scale, an elongated structure perpendicular to the flow, interpreted as an accretion disk around the central object (Cesaroni et al. 1997, 1999; Zhang et al. 1998). Previous observations at cm wavelengths have only resulted in upper limits with the exception of the $3.6\,$cm observations of Kurtz et al. 1999 who measured a flux density of $0.3\,$mJy and an upper limit to the size of $2''$. We have used the NRAO's Very Large Array (VLA)[1] to observe I20126 in the $7\,$mm and $3.6\,$cm continuum bands. The results of these observations are presented below. Throughout the paper we assume a distance to I20126 of $1.7\,$kpc (see Cesaroni et al. 1997).

2. Observations

2.1. 7 mm continuum

The $7\,$mm observations were taken on October 4, 1997 with the VLA in the DnC hybrid configuration. We used the 13 antennas equipped with $7\,$mm receivers to observe I20126 in the fast switching mode with the phase calibrator source 2005+403, using a cycle time of $120\,$sec, and observing in standard continuum mode with a total bandwidth of $100\,$MHz. Flux calibration is based on observations of 3C48, for which we assumed a flux density of $0.57\,$Jy in the $7\,$mm band. A natural weighted 256×256 pixel map was made with a pixel size of $0\farcs2$. The resulting beam size is $1\farcs7 \times 1\farcs0$ at a position angle of 80°, and the 1σ rms value in the map is $0.7\,$mJy beam^{-1}.

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

Send offprint requests to: hofner@naic.edu

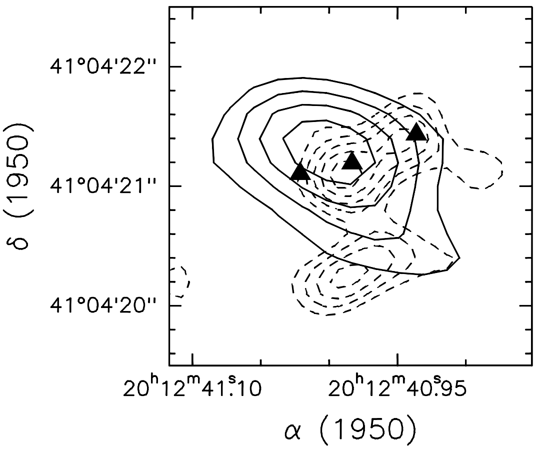

Fig. 1. Contour plot of the 7 mm continuum emission toward I20126 (solid contours). Contour levels are 1.5 to 3.9 by 0.8 mJy beam^{-1}. The dashed contours show the continuum emission at 3.6 cm with contour levels 0.03 to 0.11 by 0.02 mJy beam^{-1}. The filled triangles mark the position of the 22 GHz H_2O masers from Tofani et al. (1995).

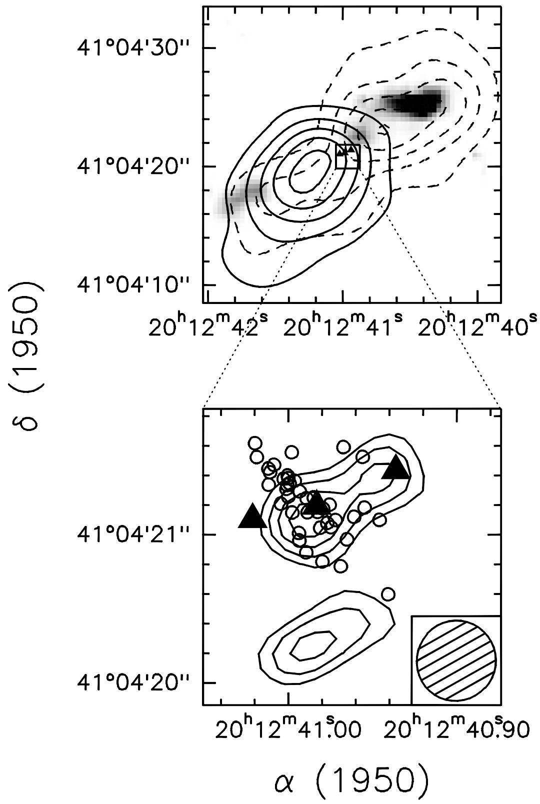

Fig. 2. *Top panel:* The bipolar molecular flow in I20126. Blue- and red-shifted HCO^+(1–0) emission is shown in solid and dashed contours respectively. Emission from the H_2 $v = 1 \rightarrow 0$ S(0) vibrational line at $2.122\,\mu$m is shown in grey scale (see Cesaroni et al. 1997 for details). H_2O masers are shown as filled triangles and the box shows the area seen enlarged below. *Bottom Panel:* 3.6 cm continuum emission (contours) with levels 0.05 to 0.11 by 0.02 mJy beam^{-1}. The filled triangles mark the position of H_2O masers and the open circles mark the peak position of gaussian fits to channel maps of the CH_3CN(5–4) transition. The synthesized beam is shown in the bottom right corner.

2.2. 3.6 *cm continuum*

On August 18, 1998 we used the VLA in the B configuration to observe the 3.6 cm continuum toward I20126. Visibility amplitude and phase were calibrated by frequent observations of the calibrator source 2005+403, and the flux density scale was set by observations of 3C48 for which we assumed a flux density of 3.29 Jy at 3.6 cm. Images with 256×256 pixels with a pixel-size of $0.''1$ were made using different weighting schemes. Our uniformly weighted map has a synthesized beam of $0.''5 \times 0.''5$ and a 1σ rms noise level of $13\,\mu$Jy beam^{-1}.

3. Results

Fig. 1 shows a contour map of the 7 mm continuum emission toward I20126. The emission is unresolved and the peak position, as determined from gaussian fitting is $\alpha(1950) = 20^h\,12^m\,40.^s99$, $\delta(1950) = 41^\circ\,04'\,21.''2$, coincident with that of the 3.3 mm continuum measured by Cesaroni et al. (1997). The total flux density is $S_{7mm} = 3.1$ mJy.

In the lower panel of Fig. 2 we show our uniformly weighted 3.6 cm continuum map in solid contours. We also show the position of the water masers measured by Tofani et al. (1995) as triangles and the peak positions of fits to channel maps of CH_3CN(5–4) from Cesaroni et al. (1997) as circles. The 3.6 cm continuum emission consists of two clearly distinct sources, the northern one being coincident with H_2O masers, CH_3CN and mm continuum emission. Both sources are clearly resolved along their major axis, and appear to be aligned in the same direction with a position angle of $\sim 117^\circ$. This orientation is identical to the direction of the bipolar molecular flow imaged in the HCO^+(1–0) transition by Cesaroni et al. (1997), which is shown in the upper panel. The H_2O masers are coincident with the northern continuum source and are also aligned along this same angle. On the other hand the structure seen in CH_3CN is oriented perpendicular to the 3.6 cm continuum emission.

In our uniformly weighted map we measure 3.6 cm flux densities of about 0.2 mJy and 0.1 mJy for the northern and southern components respectively. The northern component appears double peaked and can be well fitted with two unresolved sources of similar flux density. The southern component has a single peak; a 2-D gaussian fit shows that it is unresolved along the minor axis and has a deconvolved size of $0.''7$ along its major axis.

We also searched for 3.6 cm continuum emission at the position of the sources detected in the H_2 NIR lines by Ayala et al. (1998). No additional sources where found with a $3\,\sigma$ limit of $30\,\mu$Jy beam^{-1}.

4. Discussion

4.1. *Origin of the* 7 *mm continuum emission*

As mentioned above, the 7 mm emission in I20126 is coincident with the 3 mm emission peak measured by Cesaroni et al. (1997). The spectral index measured between 7 mm and 3 mm is 3.1 ± 0.4. This is in good agreement with the recent measurement of Cesaroni et al. (1999) of the spectral index between 3 mm and 1.3 mm of ∼2.9. Hence we conclude that the 7 mm emission arises from dust with an absorption coefficient proportional to ν.

4.2. An ultracompact H II region model

We now turn to the interpretation of the 3.6 cm continuum emission. A possible explanation of the 3.6 cm continuum emission shown in Fig. 2 is a cluster of three individual H II regions, each having a 3.6 cm continuum flux density of about 0.1 mJy. The two regions making up the northern component are unresolved, i.e. an upper limit on their size is $0\rlap{.}''2$, or 0.0017 pc. Assuming optically thin conditions with an electron temperature of 10^4 K, neglecting the absorption of ionizing photons by dust and using the tables of Panagia (1973), we find that three ZAMS stars of spectral type B3 are required to explain the observed flux density. Three B3 stars only provide a luminosity of $3000\,L_\odot$ as compared with the FIR luminosity of $1.3 \times 10^4\,L_\odot$ measured by the IRAS satellite. This reflects the well known fact that the spectral types derived under these assumptions represent lower limits. Besides the internal absorption of ionizing photons by dust, and the presence of unrelated luminous sources in the IRAS beam, a large fraction of the luminosity in I20126 could derive from accretion: indeed, according to Cesaroni et al. (1999), the latter could be $\sim 1.2 \times 10^4\,L_\odot$.

We tend to exclude that the 3.6 cm continuum emission is optically thick. From the observed brightness temperature (6.5 K) we can derive the size of the emitting source of 5.6×10^{-5} pc: this number is extremely small and even for a spectral type as late as B3 is of order of the initial Strömgren radius for densities of $2 \times 10^7 \mathrm{cm}^{-3}$. This would imply that the age of the H II regions is of order a few hundred years, a somewhat unlikely scenario. Also, the continuum spectrum must become optically thin at frequencies larger than 15 GHz, otherwise we should have detected excess emission over what is expected from dust alone at 7 mm.

4.3. An ionized jet scenario

Both 3.6 cm continuum components appear narrow and elongated in the direction of the large scale outflow in I20126. This morphology is strongly suggestive of ionized jets. In what follows, we will favor this scenario for the origin of the 3.6 cm continuum emission. In order to estimate the physical parameters of the ionized jets, we have fitted single gaussians to both northern and southern sources. Assuming a two-sided symmetric jet, we can estimate its solid angle. In Table 1, we list the deconvolved sizes, solid angles, position angles, and total flux densities based on this model. At the assumed distance of 1.7 kpc the physical dimensions of the jets are about 1300 AU along the major axis and $\leq$ 350 AU along the minor axis, so that collimation must have occurred within a few hundred AU.

What is the origin of the continuum emission in the jet scenario? Since the data presented here are presently the only detection at cm-wavelengths toward I20126, we cannot exclude a non-thermal origin of the 3.6 cm emission. However, since most radio jets detected toward highly embedded systems like I20126 are of thermal nature (e.g. Anglada 1996, but note Reid et al. 1995), we will restrict our discussion to the case of thermal radio jets. Detection of the radio emission from I20126 at other wavelengths would be extremely valuable to check this hypothesis.

Table 1. Observed jet parameters

Source	Size	$\Omega/4\pi$	PA(°)	S_ν(mJy)
North	$0\rlap{.}''9 \times \leq 0\rlap{.}''2$	$\lesssim 0.025$	120 ± 5	0.2
South	$0\rlap{.}''7 \times \leq 0\rlap{.}''2$	$\lesssim 0.04$	116 ± 6	0.1

Assuming then that the 3.6 cm emission is of thermal nature, there are two possible sources of the ionized gas in I20126. First, we consider shock induced ionization, i.e. the gas could be ionized by UV photons produced when a neutral stellar wind shocks against the surrounding high density matter. We can test this by comparing the observed fluxes with those predicted from the measured momentum rate of the large scale molecular outflow (e.g. Anglada 1996). Using Eq. (8) of Curiel et al. (1989) with a terminal wind velocity of $10^3\,\mathrm{km\,s^{-1}}$, we derive momentum rates of 0.01 and $0.004\,M_\odot\,\mathrm{yr^{-1}\,km\,s^{-1}}$ for the northern and southern source respectively. These values are quite similar to what was obtained for the ionized jet from the massive object IRAS18162-2048 (HH 80–81) by Martí et al. 1995. Because the continuum sources are unresolved along their minor axis, these numbers represent lower limits on the momentum rate. The momentum rate as estimated from the HCO^+(1–0) observations of Cesaroni et al. (1997) is $0.09\,M_\odot\,\mathrm{yr^{-1}\,km\,s^{-1}}$, much larger and thus consistent with our lower limit. Clearly, higher resolution observations which resolve the ionized jet would be extremely useful to improve this comparison. Also, note that the momentum rate derived from the HCO^+(1–0) data carries large uncertainties due to the unknown chemical abundance.

Second, the ionization could be caused by stellar UV photons. In this case we compute the total stellar Lyman continuum flux by assuming that only UV photons emitted into the solid angle of the jet contribute to the ionization while the UV photons emitted in the perpendicular plane are absorbed in the high density environment very close to the star which is possibly provided by an accretion disk. Because of dust absorption and again due to the fact that the jets are unresolved along the minor axis we obtain lower limits on the total Lyman continuum flux of 2.2×10^{45} and $6.7 \times 10^{44}\,\mathrm{s^{-1}}$ for the northern and southern jet respectively. These numbers correspond to ZAMS spectral types of B1 and B2: the expected FIR luminosity for such a system is $\sim 8000\,L_\odot$, very close to the measured FIR luminosity of I20126.

In this scenario we can also obtain a limit on the momentum rate following the theory of Reynolds (1986). Using his Eq. (19) and under the assumption of an isothermal jet of temperature 10^4 K with constant opening angle, a constant ionization fraction of 100% and a terminal jet velocity of 10^3 km s^{-1}, we find upper limits on the momentum rate of about 0.001 M$_\odot$ yr^{-1} km s^{-1}. The momentum rate derived from the HCO$^+$(1–0) observations is about two orders of magnitude larger which seems to contradict this theory. However we need to keep in mind that this comparison could be strongly affected by the uncertainty of the assumed values of wind velocity, ionization fraction and HCO$^+$(1–0) abundance.

4.4. *Water masers*

As noted above (see Fig. 2) the water masers in I20126 are coincident with the northern 3.6 cm continuum source and are aligned at the same position angle. The observations of Tofani et al. (1995) show that the water maser spots at the NW and SE edges of the continuum have narrow velocity distributions with velocities blueshifted in the SE and redshifted in the NW with respect to the bulk velocity of the molecular gas in I20126 of -3.5 km s^{-1}. The maser spot close to the maximum of the continuum emission shows a wider range of velocities, but still distributed symmetrically around the bulk velocity. Possibly the central maser spot occurs close to the collimation region, so that both blue and redshifted velocities can be observed as the molecular gas expands away from the central object, whereas the maser spots at the NW and SE edges may occur in a turbulent molecular layer surrounding the ionized jet (e.g. Raga et al. 1993, Torrelles et al. 1997) and since the jet is almost in the plane of the sky the observed radial velocities here are relatively small. Thus the distribution and velocities of the water masers lend support for the ionized jet scenario.

5. Conclusions

Our 3.6 cm observations of I20126 show a double continuum source with both components elongated in the direction of the large scale molecular outflow. The northern source is coincident with an unresolved 7 mm peak due to dust continuum emission, as well as CH_3CN emission oriented perpendicular to the cm continuum. H_2O masers are coincident with the northern continuum source, whereas none of the above tracer is present at the position of the southern source. We suggest that these observations can be explained by a double ionized jet with both jets possibly contributing to driving the large scale outflow observed in HCO$^+$, similar to what is found for the flow in L1551 IRS5 (Rodríguez et al. 1999).

If this interpretation is correct, our observations raise several interesting questions about the disk/jet system in I20126. First, what is the mechanism which has aligned the two jets? Second, in contrast to the northern jet, there is no evidence for any disk at the position of the southern jet. This raises the question of how the southern jet is collimated.

To summarize, IRAS 20126+4104 is one the most promising sources for the study of disks and collimated flows from high mass systems and we expect that further high resolution and sensitivity observations of this system will allow us to learn much about the role of disk/jets in the formation of high mass stars.

Acknowledgements. We thank S. Kurtz for help with the 7 mm observations. This project was partially supported by ASI grants ARS-96-66 and ARS-98-116 to the Osservatorio Astrofisico di Arcetri. JM is partially supported by DGICYT (PB97-0903) and Junta de Andalucía (Spain).

References

Anglada G. 1996, ASP Conference Series Vol. 93, p. 3
Ayala S., Curiel S., Raga A.C., Noriego-Crespo A., Salas A., 1998, A&A 332, 1055
Cesaroni R., Felli M., Testi L., Walmsley C.M., Olmi L., 1997, A&A 325, 725
Cesaroni R., Felli M., Jenness T., et al., 1999, A&A, in press
Curiel S., Rodríguez L.F., Canto J., et al., 1989, Astrophysical Letters and Communications 27, 299
Kurtz S., Carral P., Martí J., et al., 1999, ApJ, in preparation
Martí J., Rodríguez L.F., Reipurth B., 1995, ApJ 449, 184
Panagia N. 1973, AJ 78, 929
Raga A.C., Canto J., Calvet N., Rodríguez L.F., Torrelles J.M., 1993, A&A 276, 539
Reid M.J., Argon A.L., Masson C.R., Menten K.M., Moran J.M., 1995, ApJ 443, 238
Reynolds S.R., 1986, ApJ 304, 713
Rodríguez L.F., D'Alessio P., Wilner D.J., et al., 1999, Nature 395, 355
Tofani G., Felli M., Taylor G.B., Hunter T.R., 1995, A&AS 112, 299
Torrelles J.M., Gómez J.F., Rodríguez L.F., et al., 1997, ApJ 489, 744
Zhang, Q., Hunter, T., Sridharan, T.K., 1998, ApJ 505, L151