Astron. Astrophys. 329, 243–248 (1998)

ASTRONOMY AND ASTROPHYSICS

The ionized wind of IRAS 08159-3543

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Received 22 May 1997 / Accepted 14 July 1997

Abstract. We report the detection of cm radio emission from the ionized wind which had been suggested to exist in the inner part of the bipolar outflow around the embedded Young Stellar Object (YSO) IRAS 08159-3543. The small radio flux density, the spectral index and the unresolved size of the source are all consistent with an ionized stellar wind with a mass loss rate ($\sim 10^{-5}$ $M_\odot$/yr), slightly smaller than that predicted from the observed Hα radiation scattered in the neutral parts of the wind. This confirms that the fast flowing neutral material far out in the lobes must have been accelerated by the same mechanism at work near the luminous YSO.

The presence of an ionized wind implies the existence of a strong source of ionizing photons, which is much hotter than the star inferred from visible and NIR observations (and corresponding to a spectral type F - K). This could be an early spectral type star whose optical radiation is strongly attenuated by its surrounding disk. Alternatively, the ionizing radiation could be provided by the hot boundary layer of a highly active accretion disk surrounding a lower mass PMS star. This result is consistent with the notion, supported also by spectroscopic properties of the YSO, that the dominant source of optical and near IR radiation is a disk, whose color temperature depends on the spectral range within which it is determined.

IRAS 08159-3543, with its associated reflection nebula GN08.16.0, is one of the few cases where the inner ionized part of the wind and the outer neutral parts of a larger scale bipolar outflow can be observed simultaneously, and offers the opportunity to study the interaction of the wind with the surrounding disk in the first evolutionary stages of a YSO.

Key words: stars: formation – accretion, accretion disks – ISM: jets and outflows – H II regions – ISM: individual objects: GN08.16.0, IRAS 08159-3543

1. Introduction

A detailed high resolution optical and near IR study (Neckel & Staude 1995, hereafter NS) of the bright and compact galactic nebulosity GN08.16.0 (Neckel & Vehrenberg 1990), coinciding with the far IR source IRAS 08159-3543, has shown that this nebula contains in its center a very peculiar embedded YSO in an early stage of evolution. The near IR source, also known as IRS6/2 (Liseau et al. 1992), has been classified as a Class I object (see Lada 1987, Wilking et al. 1989, Andrè 1994 for a definition of YSO's classes) on the basis of the spectral slope s = 1.5[1] between 2 and 25 μm (Liseau et al. 1992). Class I sources have s $\geq$0, indicating a rise in the spectral energy distribution all the way up to 100 μm, have a very conspicuous IR excess and their spectrum is much broader than that of a single temperature blackbody function. From the evolutionary viewpoint, Class I sources are thought to represent accreting protostars, surrounded by luminous disks, with radii 100 - 1000 AU, and by in-falling, extended envelopes with sizes of $\sim 10^4$ AU.

The YSO itself is hidden behind huge amounts of dust ($A_V > 43$ magnitudes) distributed in a disk-like structure oriented almost edge on, which makes the central source virtually undetectable at wavelengths $< 1\mu$m. In the direction perpendicular to the disk (and nearly perpendicular to the line of sight) the extinction must be much smaller ($A_V \sim 2$), since it allows the escape of the strong Hα emission produced by the YSO and of its continuum radiation. This radiation is then reflected in two bipolar dusty lobes which expand from the YSO in the direction perpendicular to the disk. The neutral gas outflow velocity within the bipolar reflection nebula is of the order of 600 km s^{-1} and the total mass loss rate of the neutral wind is estimated to lie in the range 6 10^{-5} - 2 10^{-4} $M_\odot$/yr. This fast neutral wind causes the extended shock-excited Herbig-Haro emission throughout the large scale reflection lobes.

The presence of a disk is supported by the Hα spectroscopy. In fact, the Hα line profile, which comes from radiation emitted by the central source and scattered by dust far out in the lobes, shows a large high velocity blue shifted asymmetry. This implies that the volume emitting Hα near the YSO must be bisected by an optically thick disk which allows the scattering dust grains to see only the approaching gas, the receding gas being hidden by the bisecting disk.

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[1] 1) the spectral slope is defined as s = dlog(λF_λ)/d logλ

Detection of chromospheric FeII lines also suggests the existence of an active accretion disk around the YSO. The presence of a luminous central source is revealed by the strong optical continuum scattered in the reflection nebula, and by the far IR emission of cool dust observed by IRAS. The estimated luminosity from far IR data is 2.4 10^4 $L_\odot$. The cool dust emitting the spectrum characteristic of class I sources is located in the outer parts of the accretion disk. If IRAS 08159-3543 is truly a class I protostar, its disk-like structure could also be produced by a flattened infalling envelope such as those modeled by Kenyon et al. (1993) and Calvet et al. (1994).

Most of the outflowing material in the lobes must have been accelerated by the primary mechanism at work near the YSO, with little contribution to the outflow mass from entrained ambient material. Consequently, similar mass loss rate and velocity are expected for an eventual ionized wind in the inner part of the outflow.

Molecular emission (CO) from this IRAS source was detected by Wouterloot & Brand (1989) with T_K = 8.3 K, a radial velocity of 31.4 km s^{-1} and a relatively large linewidth of 4.5 km s^{-1}, suggesting a bipolar molecular outflow on even larger scales, though with much lower velocity.

All these aspects make this object one of the very few cases in which one can study the early stages of the interaction between a YSO and its surrounding environment, at the onset of the bipolar flow. The other outstanding example is the bipolar nebula S 106 (Felli et al. 1984), which, however, seems to be in a more advanced evolutionary stage since a well developed extended bipolar HII region is present in this case.

The existence of an ionized wind close to the YSO in addition to the more extended shock-ionized gas in the Herbig Haro nebulosities detected in the outflow lobes (the total extent of the nebula is of the order of 30$''$) was postulated by NS in order to account for the broad Hα line scattered in the outflow lobes. But very little information can be found in the literature on the cm wavelength radio continuum emission from this ionized gas, i.e. in a wavelength range free from dust emission. An upper limit of 100 mJy from the position of GN 08.16.0 is all that can be derived from the Parkes 5 GHz survey of the galactic plane, but this limit has little relevance for the ionized wind, given the small flux densities expected (Panagia & Felli 1975), and can only exclude the presence of a diffuse bright HII region around the YSO - in obvious accordance with the optical spectroscopic results of NS.

The detection of an unresolved cm radio continuum emission from the position of the YSO (identified by NS with a bright K band source located at the center of the bipolar nebula), would support the ionized wind hypothesis put forth by NS, and would provide more stringent constraints on the spectral type of the central star (if the star is providing the ionizing radiation) or on the structure of the circumstellar accretion disk (if the ionizing photons are emitted by a hot boundary layer).

For a proper identification of the radio continuum emission with an ionized wind two conditions must be satisfied (Panagia & Felli 1975): the spectral index (defined as $S_\nu = \nu^\alpha$) must match the predicted value of α = 0.6, and the source size must be small, $\leq 1''$. In fact, for a mass loss rate of 10^{-5} $M_\odot$/yr and wind velocity of 600 km s^{-1} the expected angular size at a distance of 4.3 kpc (following NS) at 8.4 GHz is 0.008$''$. These two conditions should enable us to discriminate the radio continuum emission of an ionized wind from that of the diffuse Herbig Haro nebulosities.

With this in mind we observed the source at two frequencies with the VLA[2] in the BnA configuration (the most extended configuration suitable for observing objects in the southern sky). In this paper we report the detection of an unresolved radio source at the position of the YSO and discuss the implications of this result in the framework of an ionized wind.

2. Observations

The observations at 8.4 and 15 GHz were made with VLA on 1997 Jan 28. Although the declination of the source is quite low ($-35°$), GN08.16.0 does rise above 15° elevation for about 4 hours around meridian transit, which was our total integration time. With a one hour integration time at 15 GHz we expected to detect a 1 mJy point source with a signal to noise ratio of 10. At 8.4 the VLA sensitivity is better, but the wind emission is weaker. As a final compromise split between the two frequencies 46 minutes were spent at 8.4 GHz and 67 at 15 GHz. The resolutions at the two frequencies were 0.7"x1.0" and 0.4"x0.7", respectively. The calibration source was J0828-375. Due to poor phase stability, the first 30 minutes worth of data were edited out. Extended structures with size greater than 15" were filtered out by the instrument response.

3. Results

In Fig. 1 the two radio maps at 8.4 and 15 GHz are shown. An unresolved radio source is clearly detected at 8.4 GHz at the position $\alpha(1950) = 08^h\ 15^m\ 58.64^s$ and $\delta(1950) = -35°\ 43'\ 23.9''$. The peak flux density at 8.4 GHz is 406 $\pm$ 27 μJy and an upper limit to the source size is $\leq$0.6$''$($\leq$2.5 10^3 AU). In the 15 GHz map the noise level is much higher, but an unresolved source can still be detected at the same position of the 8.4 GHz source, with peak flux 470 $\pm$ 100 μJy (4.7 σ). No diffuse emission is evident in our data. To compare radio and near IR structures, an accurate astrometry of the K-band near IR image of NS has been performed (see Testi 1993 for a complete description of the astrometric calibration procedure). The overlay of the 8.4 GHz source on the K-band image is shown in Fig. 2. The coincidence of the radio source with the YSO (namely, the eastern K-band peak in figure 1 of NS) is extremely good and it points out that the radio source is indeed at the center of the bipolar structure. The position of the IRAS source coincides, within the error, with the YSO.

The spectral index α is 0.25. Given the large errors on the 15 GHz flux, the extreme possible values of α within the uncertainties are 0.7 and -0.27. As amply illustrated by Skinner et al.

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

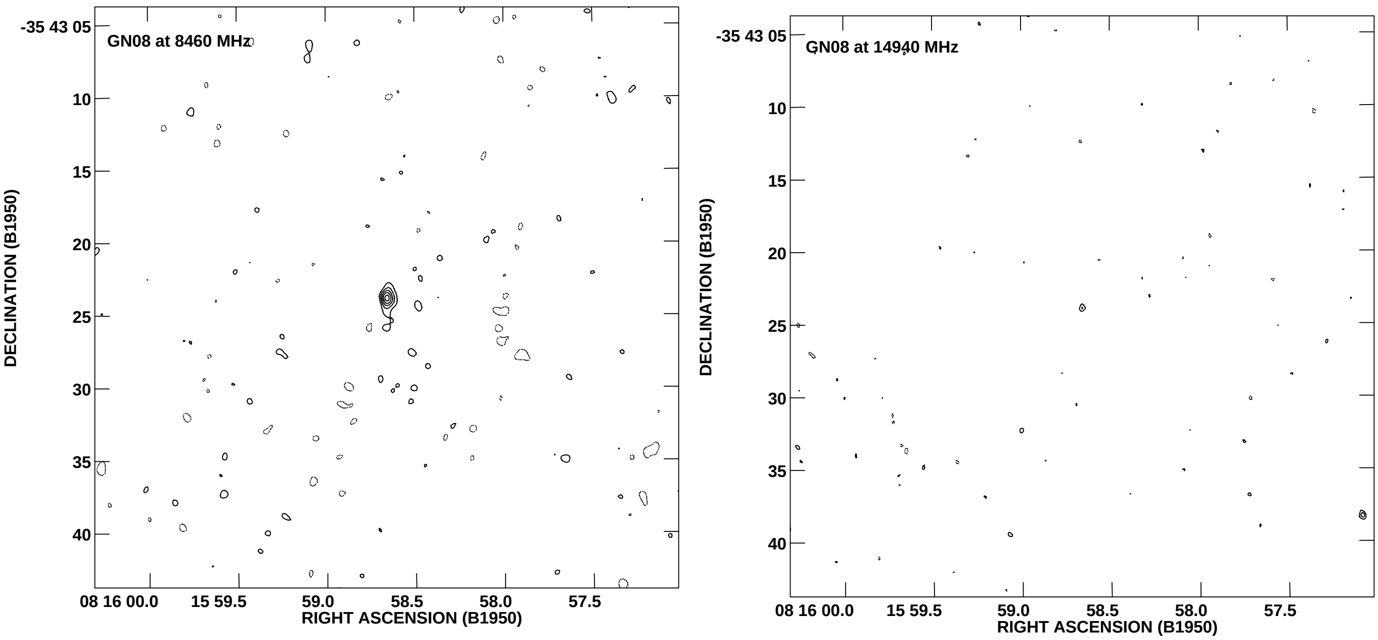

Fig. 1. On the left: the 8.4 GHz map. Contours are drawn at −75, 75, 150, 225, 300, and 375 μJy/beam. On the right the 15 GHz map. Contours are drawn at −300, 300 and 450 μJy/beam.

(1993) for the radio continuum detections of Herbig Ae/Be stars, there are several alternative ways to explain the radio emission in these type of objects, besides the ionized wind model which seems to be the most probable explanation. For instance, the spectral index is also consistent with shock-ionized collimated jets (Reynolds 1986) which are often found at the centre of bipolar molecular outflows associated with low luminosity YSOs (Anglada 1996). This possibility might be supported by the bipolarity of the neutral wind and the existence of HH emission features. Since highly collimated jets are more efficient (less optically thick) than spherical winds at producing radio emission, the derived mass loss rate would be significantly lower in this hypothesis. We do not see a jet structure in IRAS 08159-3543. However, since the typical size of the observed jets is ∼500 AU (Anglada 1996), at the distance of our source the angular size would be ≤0.1″, i.e. not in contradiction with our upper limit to the source size. Although less likely, from the radio data alone a nonthermal gyrosyncrothron model cannot be excluded either (for a review see Andrè 1996). However, since the spectral index of an ionized wind ($\alpha = 0.6$) is close to the nominal one and within the extreme values, and also considering the unresolved size, the high luminosity (and presumably the high supply of ionizing radiation) and the morphology of the source discussed by NS, in the following discussion we shall consider only the ionized wind hypothesis.

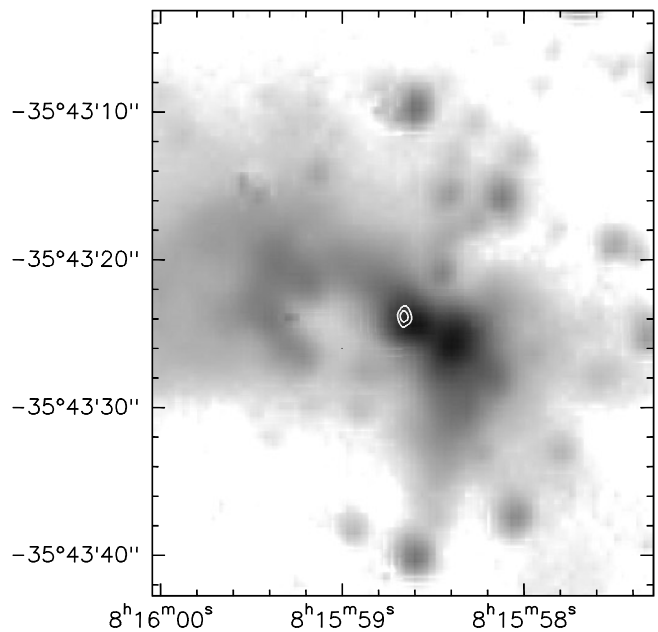

Fig. 2. Overlay of the 8.4 GHz map on the K-band image of NS.

We note that the source has also been detected at 1.3 mm by Chini (quoted in Liseau et al. 1992) with a flux density of 243 ± 34 mJy (with the 15 m SEST MPIfR bolometer, a 24″ beam, and a 50 GHz bandwidth). This emission must come predominantly from the dust in the disk surrounding the YSO and should not be confused with that coming from the ionized wind, since the extrapolated wind emission at 1.3 mm is less than 10 mJy. Vice-versa, the extrapolated disk flux density at 15 and 8.4 GHz (using a ν^4 dependence typical of optically thin dust emission) is of the order of 1 μJy, much less than the observed value and, presumably, coming from a more extended source.

4. Discussion

4.1. The ionized wind

The radio flux density from an ionized wind can be expressed as (Panagia & Felli 1975, Felli et al. 1982):

$$S_\nu = 0.01(\nu_{8.4})^{0.6}(\dot{M}_{-8})^{4/3}(v_2)^{-4/3}(d)^{-2} \quad mJy$$

where $\nu_{8.4}$ is the frequency in units of 8.4 GHz, $\dot{M}_{-8}$ is the mass loss rate in 10^{-8} $M_\odot$/yr, v_2 is the terminal wind velocity in units of 100 km s^{-1}, d the distance in kpc (a temperature of 10^4 K for the ionized gas and an average atomic weight per electron of 1.2 has been assumed). The equation is valid only in the isotropic case, which we know not to be our case due to the presence of the bisecting disk. However, for small anisotropies the variations of the radio parameters (size, spectral index and flux density) are very small since they are determined essentially by the electron density distribution (which is r^{-2} in the constant velocity case) and not much by possible anisotropies of the wind (Schmid-Burgk 1982). Consequently, it should be safely applicable even in our case.

With a terminal wind velocity of 600 km s^{-1} the mass loss rate becomes 0.9 10^{-5} $M_\odot$/yr, slightly lower but amply consistent with the value estimated in a completely independent way by NS.

The difference between the two estimates (if at all significant) is not unexpected. In fact, if, as NS have suggested, there is a bisecting disk around the star, we expect that the outer parts of the disk will be self-shielded from the ionizing radiation. This neutral part of the disk may contribute to the neutral wind observed by NS, but not to the mass loss rate estimated from the radio data. The presence of a wind component which is neutral *ab initio* is indicated by the fact that the scattering dust far out in the lobes is flowing outwards at 600 km s^{-1}. This fast dust must have been carried along by the primary wind in a relatively cool acceleration region, where dust grains can survive.

A more direct comparison between the observed radio flux and the Hα luminosity can also be made. From the NS data L(Hα) = 94 $L_\odot$, which corresponds to I(Hα) = 1.66 10^{-16} erg cm^{-2} s^{-1}. Using equations 5 and 6 of Felli et al. (1982), S_ν and I(Hα) can be directly compared, provided some properties of the wind and of the YSO are known (e.g. the velocity in the inner part of the wind where the Hα emission is produced, the velocity in the outer parts of the ionized wind and the stellar radius). Using the terminal wind velocity and the mass loss rate given by NS and assuming a stellar radius of 5 $R_\odot$ and an inital wind velocity of 100 km s^{-1}, S_ν and I(Hα) are consistent with each other.

In conclusion, both indications support the hypothesis that the ionized wind and the neutral bipolar outflow originate from the same accelerating agent, likely an accretion disk around the YSO.

Why does the wind become neutral towards the poles of the disk (as implied by the NS observations)? A partial explanation may come from the fact that ionizing photons N_L^* are predominantly absorbed in the inner higher density optically thick part of the wind. If the wind ionization is close to critical, almost all ionizing photons are absorbed within the wind ($N_L^* = N_{Lcrit}$, see Felli & Panagia 1981), and only a small fraction are left to ionize the outer parts. The critical condition, i.e. when the stellar ionizing photons precisely match the amount required to keep the wind ionized, are defined by the equation:

$$N_{Lcrit} = 3\ 10^{43}\ \dot{M}_{-8}^2\ v_2^2\ r_{10}^{-1} \quad photons\ sec^{-1}$$

where r_{10} the stellar radius in 10 $R_\odot$.

Another partial explanation may come from the presence of dust within the wind. The inner part of the wind will be essentially dust free, due to the high dust equilibrium temperature close to a hot source and the sublimation of dust for temperatures exceeding 1500 K (for an O9.5 ZAMS star the distance at which T_{dust} = 1500 K corresponds to 2 10^3 stellar radii). At larger distances dust will survive the radiation field and will be capable of absorbing ionizing photons in excess of the critical value.

It must also be remembered that the entire complex is located within a CO molecular cloud (Wouterloot & Brand 1989). Consequently at large distances from the YSO (few arcsecs or ~ 0.1 pc) there is plenty of ambient molecular gas to absorb any excess ionizing photons. In fact, if N_L^* were much larger than N_{Lcrit} (or, alternatively, if the mass loss rate were much less than the critical value) a large surplus of ionizing photons (i.e. not used up to keep the wind ionized) would be available and a spectacular bipolar ionized nebula, similar to S 106, would be created. It should be remembered that for the same amount of ionizing photons the radio flux from an optically thin HII region is about two orders of magnitude larger than that of an ionized wind, because of strong self absorption effects in the wind. Hence, even a small N_L^* excess with respect to N_{Lcrit} can create a spectacular HII region. Since this does not seem to be the case, we must conclude that N_L^* is close to, but lower than, N_{Lcrit}. However, N_L^* cannot be much smaller than N_{Lcrit} since in this case the optically thin part of the ionized wind (at a distance $\geq 10^3$ stellar radii) would be absent and the ionized wind radio emission would be strongly reduced (Simon et al. 1983).

In conclusion, the radio continuum aspect of a YSO surrounded by an ionized wind and embedded in a larger scale molecular cloud is entirely determined by the ratio N_L^*/N_{Lcrit} (or, alternatively, by the ratio of the mass loss rate with respect to the critical mass loss rate). If $N_L^*/N_{Lcrit} \ll 1$, essentially no radio emission is detectable, since the ionization front does not reach the outer parts of the wind, if $N_L^*/N_{Lcrit} \sim 1$ only a weak unresolved source (the ionized wind) is observed, and if $N_L^*/N_{Lcrit} \gg 1$ a bright (and much more extended) HII region is observed plus the weak contribution form the unresolved source associated with the ionized wind.

Comparison of GN 08.16.0 with S 106 suggests that this ratio is lower than 1 in the earliest stages (e.g. GN 08.16.0), either because the N_L^* is lower than the value the star attains when it is on the main sequence or because the mass loss rate is much greater in the earliest phases of star formation, or both, and then increases in subsequent stages (e.g. S 106) for the opposite reasons, i.e. an increase of N_L^* and/or a decrease of the mass loss rate.

4.2. The spectral type of the YSO

The colors and reddening arguments had led NS to estimate the spectral type of the YSO to be between F0 and G0. The detection of an ionized wind requires a much earlier spectral type for the exciting star (in the hypothesis that the ionizing radiation comes from a ZAMS star).

In fact, in the assumption that $N_L^*/N_{Lcrit} \sim 1$, N_L^* can be derived from the observed radio flux using equation 15 of Felli & Panagia. With the additional hypothesis of a constant wind velocity N_L^* turns out to be 8.5 10^{47} photons s^{-1}. According to Panagia (1973) this corresponds to an O9.5 ZAMS star. A star of this spectral type would also be in very good agreement with the luminosity derived by NS, i.e. 2.4 10^4 $L_\odot$.

The optical spectral identification of the YSO is then determined not by the stellar continuum, which is strongly attenuated by internal extinction in the dusty wind (NS), but by the continuum emitted in the cooler outer parts of the disk.

An alternative hypothesis is that the ionizing radiation comes from a hot boundary layer at the inner edge of the accretion disk, where about half of the accretion luminosity is radiated away. This situation would also account for the fact that the luminosity obtained above from the radio continuum is nearly equal to that derived by NS from the infrared data. The radius of this boundary layer is $R_{bl} \approx 1.4 R_*$ (see Frank et al. 1985).

To test this hypothesis, let us consider a central star with M_* = 2$M_\odot$, R_* = 2$R_\odot$. We then have to assume that essentially the entire observed luminosity is due to accretion:

$$L_{acc} = (GM_*\dot{M})/R_* = 4 \times 10^4 L_\odot$$

This implies an accretion rate $\dot{M}_{acc} = 1.3 \times 10^{-3} M_\odot$/yr. This high mass accretion rate is consistent with the notion that the fast dusty wind observed far out in the reflection lobes is driven by the active disk: the ratio of mass loss rate in the wind to mass accretion rate onto the star would then be $\dot{M}_{wind}/\dot{M}_{acc} \approx 0.05 - 0.1$, which is consistent with the value predicted by the disk-driven wind model (Pelletier & Pudritz 1992).

Half of the accretion luminosity (or $2 \times 10^4 L_\odot$) is emitted by the boundary layer, whose area is $A_{bl} = \pi R_*^2(1.4^2 - 1) = 1.510^{22}$ cm^2.

A rough estimate of the temperature of the boundary layer is then: $T_{bl} = (L_{bl}/(A_{bl}\sigma))^{0.25}$ = 97500 K, which is more than is needed to explain the observed radio continuum in terms of a wind emitted by an accretion disk, whose inner parts are photoionized by a hot boundary layer.

Again, the optical spectral identification of the YSO is determined not by the light emitted by the boundary layer, but rather by the cooler outer parts of the disk. Also the FU Ori phenomenon is usually explained in these terms: also in this class of objects the spectral type depends on the wavelength range used for its determination. In the optical range, FU Ori stars have the spectral type G - K, as found by NS also for IRAS 08159-3543.

5. Conclusions

An unresolved radio source has been detected at centimeter wavelengths in the inner part of the bipolar outflow around the YSO IRAS 08159-3543. The small radio flux density (0.4 Jy), the spectral index (0.25) and the unresolved size of the source ($\leq 0.6''$) are all consistent with an ionized stellar wind with the mass loss rate ($\sim 10^{-5}$ $M_\odot$/yr), which is a fraction of the total mass loss rate derived from the analysis of the Hα radiation scattered in the neutral parts of the bipolar lobes. This result confirms that the fast flowing neutral material far out in the lobes must have been accelerated by the same mechanism at work near the YSO.

If the wind is ionized by an embedded ZAMS star, its spectral type must be O9.5, much earlier than the spectral type derived from the colors of the system in the optical range. Alternatively, we are observing a star-disk system, whose luminosity is provided essentially by accretion within the disk onto a lower mass star. The wind is then driven by the accretion disk. The inner part of the wind is ionized by the radiation emitted by the hot layer at the boundary between the star and its accretion disk. The high accretion rate required in this case would imply that we are observing the source in a short-lived transient stage of protostellar evolution - in accordance with the other very peculiar properties of this luminous embedded YSO.

Acknowledgements. We thank Leonardo Testi for making the astrometry of the K-band image and the overlay with the radio map, and Rick Hessman for clarifying comments.

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