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RADIO SOURCES EMBEDDED IN THE DENSE CORE B59, THE "MOUTHPIECE" OF THE PIPE NEBULA

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RESUMEN

Presentamos observaciones de continuo realizadas con el Very Large Array a 8.3 GHz del núcleo denso B59 en la nebulosa de la Pipa. Detectamos seis fuentes compactas, de las cuales cinco están asociadas a las cinco fuentes más luminosas en 70 μm en la región, mientras que la fuente restante es probablemente extragaláctica. Proponemos que la emisión en radio es libre-libre y procede de los vientos ionizados presentes en estas protoestrellas. Discutimos el impacto cinemático de estos vientos en la nube. También proponemos que estos vientos son ópticamente gruesos en radio pero ópticamente delgados en rayos X y esta característica puede explicar porque los rayos X de la magnetósfera se detectan en tres de las fuentes, mientras que la emisión de radio está probablemente dominada por emisión libre-libre de las capas externas del viento.

ABSTRACT

We present Very Large Array continuum observations made at 8.3 GHz toward the dense core B59, in the Pipe Nebula. We detect six compact sources, of which five are associated with the five most luminous sources at 70 μm in the region, while the remaining one is probably a background source. We propose that the radio emission is free-free from the ionized outflows present in these protostars. We discuss the kinematical impact of these winds in the cloud. We also propose that these winds are optically thick in radio but optically thin in X-rays, and that this feature can explain why X-rays from the magnetosphere are detected in three of them, while the radio emission is probably dominated by the free-free emission from the external layers of the wind.

Key Words: ISM: individual objects (B59) — radio continuum: stars — stars: pre-main sequence

1. INTRODUCTION

The Pipe Nebula is a nearby ($\sim$130 pc), massive ($\sim 10^4\ M_\odot$) molecular cloud (Lombardi, Alves, & Lada 2006; Onishi et al. 1999) located in the southern edge of the Ophiuchus constellation that extends over $\sim 6^\circ$ in the plane of the sky. Onishi et al. (1999) identified 14 $C^{18}O$ cores within the Pipe Nebula. Of these, only the core associated with B59 (the "mouthpiece" of the Pipe Nebula) is known to have active star formation. Onishi et al. (1999) reported a CO outflow toward the center of the B59 core. There are several Hα emission line stars in or near the B59 core (Cohen & Kuhi 1979; Herbig & Bell 1988; Kohoutek & Wehmeyer 2003; Herbig 2005). Conclusive evidence of star formation was provided by Brooke et al. (2007) who, as part of the Spitzer c2d Survey of Nearby Dense Cores, detected an embedded cluster with at least 20 candidate low-mass young stars. More than 130 dust extinction cores have been identified in the Pipe Nebula and only B59 shows obvious signposts of star formation (Forbrich et al. 2009). There are now observations of B59 in several wavelengths and in this paper we present the analysis of sensitive, high angular resolution radio continuum observations made at 3.6 cm, to complement our understanding of this region.

2. OBSERVATIONS

The deep infrared extinction map of Román-Zúñiga, Lada, & Alves (2009) shows that the densest

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TABLE 1

RADIO CONTINUUM 3.6 CM SOURCES IN THE B59 DENSE CORE

No.	Position[a]		Flux Density[b]	Counterparts[c]
	α(J2000)	δ(J2000)	(mJy)	
1	17 11 13.43	−27 27 40.1	0.33 ± 0.06	Extragalactic?
2	17 11 17.26	−27 25 08.6	0.28 ± 0.05	2MASS J17111726-2725081, [BHB2007] 7
3	17 11 21.55	−27 27 42.0	0.23 ± 0.04	2MASS J17112153-2727417, [BHB2007] 9, 2XMMi J171121.5-272741
4	17 11 22.16	−27 26 01.9	0.24 ± 0.04	[DCE2008] 023, [BHB2007] 10
5	17 11 23.11	−27 24 32.4	0.63 ± 0.05	2MASS J17112318-2724315, [BHB2007] 11, 2XMMi J171123.0-272432
6	17 11 27.00	−27 23 47.9	0.26 ± 0.05	2MASS J17112701-2723485, [BHB2007] 13, 2XMMi J171127.0-272348

[a]Positional error is estimated to be $0\rlap{.}''5$.

[b]Total flux density corrected for the primary beam response.

[c]2MASS = Cutri et al. (2003); [BHB2007] = Brooke et al. (2007); 2XMMi = Watson et al. (2009), see also `http://xmmssc-www.star.le.ac.uk/Catalogue/xcat_public_2XMMi-DR3.html`; [DCE2008] = Dunham et al. (2008).

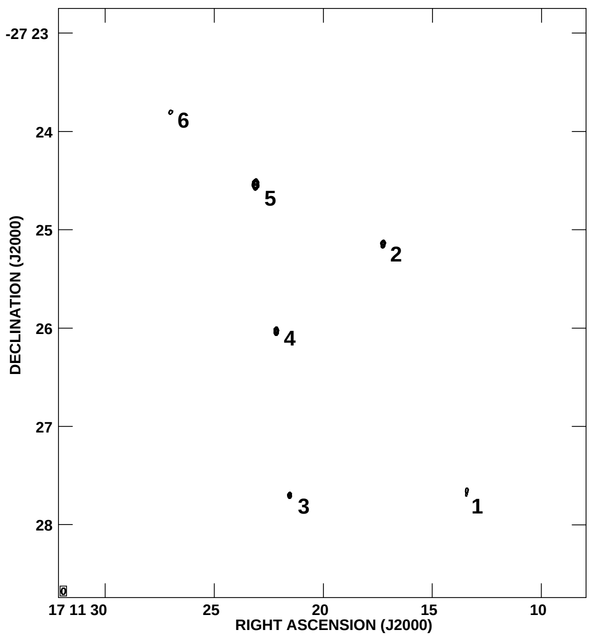

Fig. 1. VLA contour image of the 3.6 cm continuum emission toward B59. The image was made with natural weighting to optimize the sensitivity of the image. Contours are −5, 5, 6, 8, 10, 12, 15, 20, and 30 times 14.5 μJy, the rms noise of the image. The synthesized beam, shown in the bottom left corner, has half power full width dimensions of $3\rlap{.}''99 \times 2\rlap{.}''34$, with the major axis at a position angle of −3°. The six sources detected are numbered as in Table 1.

part of the B59 core has an irregular shape and extends over ∼5′. Thus, a single pointing with the Very Large Array (VLA) of the National Radio Astronomy Observatory[3] at 3.6 cm is sufficient to cover the densest part of B59. In the archives of the VLA we found unpublished observations made in 2004 February 12 at 3.6 cm in the C configuration, under project AA290. These data were edited and calibrated using the software package Astronomical Image Processing System (AIPS) of NRAO. The flux calibrator was 1331+305, with an adopted flux density of 5.23 Jy. The gain calibrator was 1626−298, with a bootstrapped flux density of 1.749 ± 0.003 Jy.

We detected a total of six sources in the field. These sources are shown in Figure 1 and their parameters are listed in Table 1.

3. DISCUSSION

3.1. *Association of the Radio Sources with Embedded Stars*

The six sources detected have flux densities of 0.23 mJy or more. In a solid angle of about 30 arcmin^2 we expect *a priori* 0.5 background sources (Windhorst et al. 1993; Fomalont et al. 2002) above 0.23 mJy. Then, we can safely conclude that most of the sources are associated with B59, with perhaps one of them being a background source. This statistical estimate is corroborated by the existence of infrared counterparts to five of the radio sources: numbers 2, 3, 4, 5, and 6. Remarkably, these five radio sources are spatially associated with the five most luminous sources at 70 μm detected by Brooke et al. (2007) and located within 0.1 pc of the peak of the molecular emission. Three of the radio sources are associated with XMM X-ray sources (see Table 1). As a consequence, we propose that VLA 1 is

[3]The NRAO is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

a background extragalactic source, while the remaining five VLA sources (numbers 2 to 6) are associated with the five most luminous sources at 70 μm (corresponding, respectively, to the sources 7, 9, 10, 11, and 13 of Brooke et al. 2007). The brightest of the radio sources (VLA 5) is also the youngest, being classified as Class 0/I (Brooke et al. 2007), and it is also detected at 1.3 mm (Reipurth, Nyman, & Chini 1996). Finally, it appears to be the exciting source of the best defined CO outflow in the region (Duarte-Cabral et al. 2012).

3.2. *The Nature of the Radio Emission*

Low mass young stars can be radio continuum emitters by two main mechanisms. Thermal free-free emission can originate in the partially ionized circumstellar material, usually tracing the base of outflowing gas. On the other hand, non-thermal gyrosynchrotron radiation can be produced in the magnetically-active corona of some young stars.

These two types of radiation can be differentiated observationally by their particular characteristics. Thermal free-free radiation is usually steady or shows slow time variations (with timescales of years), with a spectral index $\gtrsim -0.1$, and with no polarization. In contrast, gyrosynchrotron radiation can show variation timescales of hours to days and spectral indices ranging between -2 and 2. It can also show significant levels of circular polarization (e.g., Gómez et al. 2008).

Unfortunately, the available data correspond to only one epoch and one frequency, so most of the criteria to distinguish between both mechanism cannot be applied. We searched for circular polarization in the sources, setting 3σ upper limits of $\sim$0.03 mJy at the center of the image. This implies typical upper limits of 5–10% for the circular polarization. This lack of circular polarization favors, although not in a definitive way, a free-free nature for the emission. We will tentatively assume that the emission is indeed free-free mostly on the basis of two arguments. The first is the association of the radio sources with the brightest 70 μm sources. While the strengh of the gyrosynchrotron is not known to be correlated with the stellar luminosity, it is well known that the free-free radio continuum is indeed correlated with the stellar luminosity (e.g. AMI Consortium et al. 2011). The radio luminosity of the sources detected in B59 is indicative of stars with a bolometric luminosity of $\sim$0.5 $L_\odot$ (AMI Consortium et al. 2012), and this is consistent with the values found for the embedded stars (Riaz et al. 2009; Covey et al. 2010). The second argument is that the stellar sources are mostly Classes 0 to II (Brooke et al. 2007), where gyrosynchrotron emission is rare, being present more frequently in the more evolved Class III sources (Dzib et al. 2013).

3.3. *Effect of the Stellar Outflows on the Cloud*

Under assumption of free-free emission, we can use the correlation between centimeter radio continuum and molecular momentum rate (e.g., Rodríguez et al. 2008) to estimate whether the outflows being traced by the radio continuum can play a role in the disruption of the B59 molecular core. We estimate that each star injects on average a momentum rate of 8×10^{-6} $M_\odot$ yr^{-1} km s^{-1}, for a total of 4×10^{-5} $M_\odot$ yr^{-1} km s^{-1} adding the effect of the five stars.

The mass of the nuclear region of B59 is estimated from a near-IR dust extinction map to be 18.9 $M_\odot$ (Román-Zúñiga et al. 2012). To accelerate this mass to velocities of order 1 km s^{-1}, we need a timescale of $\sim 5 \times 10^5$ years for the winds, as implied by the radio observations. This acceleration is expected to disrupt, or at least significantly perturb, the cloud. Covey et al. (2010) estimate a median stellar age of 2.6 ± 0.8 Myr for B59. We then expect the cloud to be perturbed by the outflows. Duarte-Cabral et al. (2012) have studied the molecular kinematics of the cloud and conclude that most of it consists of cold and quiescent material, mostly gravitationally bound, with narrow line widths. However, they also conclude that the impact of the outflows is observed close to the protostars as a localized increase of both C^{18}O line widths (from $\sim$0.3 km s^{-1} to $\sim$1 km s^{-1}), and ^{13}CO excitation temperatures (by 2–3 K). It is possible that a significant fraction of the stellar wind's momenta has gone into slowing the collapse of the region, rather than in feeding expansion motions. It is also possible that the wind's momenta goes into accelerating a small fraction of the gas to high velocities, while leaving most of the cloud relatively unperturbed. Duarte-Cabral et al. (2012) estimate that the total momentum flux of the outflows in the cloud is 2.7×10^{-4} $M_\odot$ yr^{-1} km s^{-1}, about five times larger than the total momentum flux estimated from the radio continuum. This difference is probably due to the uncertainties involved in the estimates, but it could also suggest that the stellar winds were stronger in the past, since the outflows are the fossil record of the effect of the winds on the molecular cloud.

3.4. *X-ray Emission*

Of the five radio sources associated with young stars, we find that three have also associated X-ray emission detected with XMM (see Table 1). According to the Guedel-Benz relation (Guedel & Benz 1993) there is an intimate connection between the nonthermal, energetic electrons causing the gyrosynchrotron radio emission and the bulk plasma of the corona responsible for thermal X-rays. In other words, the presence of X-ray emission is expected to correlate with radio non-thermal emission. However, we argued previously that the observed radio emission has a thermal nature.

A possible explanation for this situation is that the X-ray emission from the corona can penetrate the stellar wind and can be detected by an external observer, while the non-thermal radio emission produced in this same region is absorbed by the free-free opacity of the stellar wind. Then, in the radio we detect only the thermal (free-free) emission from the wind itself.

To test this possible explanation, we estimate the radio and X-ray opacities expected for the winds of these young stars. The opacity along a line of sight that points from the observer to the center of the star is given by

$$\tau_\nu(R) = \int_R^\infty \kappa_\nu dr,$$

where κ_ν is the absorption coefficient, dr is the increment of pathlength, and R is the radial distance with respect to the center of the star, of the point considered.

At radio wavelengths, the absorption coefficient of the free-free process is given by (Panagia & Felli 1975)

$$\left[\frac{\kappa_\nu}{\mathrm{cm}^{-1}}\right] = 1.06\times10^{-25}\left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-1.35}\left[\frac{\nu}{\mathrm{GHz}}\right]^{-2.1} \times\left[\frac{n_e}{\mathrm{cm}^{-3}}\right]^{2}.$$

The electron density is related to the parameters of the stellar wind by

$$n_e(r) = \frac{\dot{M}}{4\pi\ r^2\ V_\infty\ \mu\ m_{\mathrm{H}}},$$

where $\dot{M}$ is the mass loss rate, r is the radius of the point considered, V_∞ is the terminal velocity of the wind, μ is the mean atomic weight per electron, and m_{H} is the mass of the hydrogen atom. Assuming that hydrogen and helium are once ionized in the wind and following the treatment of Panagia & Felli (1975), we find that the radius at which $\tau_\nu(R_{\mathrm{thick}}) = 1$, that approximately defines the region inside which the wind is optically thick, is given by

$$\left[\frac{R_{\mathrm{thick}}(\nu)}{R_\odot}\right] = 8.7\times10^{2}\left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-0.45}\left[\frac{\nu}{\mathrm{GHz}}\right]^{-0.7} \times\left[\frac{\dot{M}}{10^{-8}\ M_\odot\ \mathrm{yr}^{-1}}\right]^{2/3}\left[\frac{\mu}{1.2}\right]^{-2/3}\left[\frac{V_\infty}{100\ \mathrm{km\ s}^{-1}}\right]^{-2/3}.$$

Assuming an isotropic wind with a terminal velocity of 200 km s^{-1} (the escape velocity of a star with a mass of 0.5 $M_\odot$ and a radius of 4 $R_\odot$), $\mu = 1.2$, $T_e = 10^4$ K, and an 8.3 GHz flux density of 0.3 mJy, that is located at a distance of 130 pc, using the formulation of Panagia & Felli (1975) we derive a mass loss rate of $\dot{M} = 1.2\times10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. We then derive

$$R_{\mathrm{thick}}(8.3\ \mathrm{GHz}) \simeq 140\ R_\odot.$$

This result implies that any emission from the stellar magnetosphere will not be detected at radio wavelengths.

In the X-rays, the most important process to attenuate the emission is photoelectric absorption. To account for this effect on κ_ν it is necessary to know the abundances of different (metallic) species. In the present paper we fit as $\kappa(E) = 50(E/\mathrm{keV})^{-2}\ \mathrm{cm}^{-2}\ \mathrm{g}^{-1}$ the dependence published by Leutenegger et al. (2010; their Figure 7)[4]. This fit is valid for $E \geq 0.6$ keV. Integrating the optical depth from the observer up to a distance R_{thick} where $\tau = 1$, we obtain that

$$\left[\frac{R_{\mathrm{thick}}(X)}{R_\odot}\right] = 3.6\left[\frac{\dot{M}}{10^{-8}\ M_\odot\ \mathrm{yr}^{-1}}\right]\left[\frac{V_\infty}{100\,\mathrm{km\ s}^{-1}}\right]^{-1} \times\left[\frac{E}{\mathrm{keV}}\right]^{-2}.$$

Using $\dot{M} = 1.2\times10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ and $V_\infty = 200\ \mathrm{km\ s}^{-1}$ we derive that at $E = 1$ keV,

$$R_{\mathrm{thick}}(X) \simeq 2\ R_\odot.$$

During its main accretion phase, a solar-mass protostar is expected to have a radius of about 4 $R_\odot$ (Masunaga & Inutsuka 2000). Thus, we find that at $E \gtrsim 1$ keV the wind is optically thin, allowing us to detect the X-rays produced in the magnetosphere.

This interpretation can be tested by observations in the sub-mm range, which, in principle, will penetrate the wind and allow the detection of non-thermal radiation at those short wavelengths.

[4]In this case, $\kappa(E)$ is assumed to be constant throughout the wind. However, this assumption is relaxed in recent studies of the ζ-Puppis wind (Hervé, Rauw, & Nazé 2013).

4. CONCLUSIONS

In this paper we studied the radio emission from compact sources in the B59 dark core. We report the detection of six sources at 8.3 GHz. We propose that one of these sources is probably a background object, while the other five are associated with the five most luminous sources at 70 μm in the region (Brooke et al. 2007). We argue that the radio emission from these five sources is most probably free-free from their ionized winds. We propose that these outflows have significantly affected the kinematics of the core, although this effect seems to be concentrated close to the protostars. Finally, we discuss why three of the five sources have detected X-ray emission but apparently lack non-thermal radio emission. We propose that the winds are optically thin in X-rays, but optically thick in the radio, and that this explain the detection of X-rays from the magnetosphere, while the radio emission is dominated by the optically-thick thermal emission from the wind. Interestingly, even when the emission mechanisms of the X-rays and radio emission in these stars are independent, they still fit the Guedel & Benz (1993) relation, suggesting that stellar winds may be a significant source of contamination in this relation.

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