Circularly polarized radio emission from an X-ray protostar

Eric D. Feigelson, Lee Carkner

Department of Astronomy and Astrophysics, Pennsylvania State University,

University Park, PA 16802

Electronic mail: edf@astro.psu.edu, carkner@astro.psu.edu

Bruce A. Wilking

Department of Physics and Astronomy, University of Missouri-St. Louis,

St. Louis MO 63121

Electronic mail: bruce@newton.umsl.edu

Received ____________________; accepted ____________________

ABSTRACT

IRS 5, an embedded young stellar object in the nearby Corona Australis molecular cloud, was recently detected as an X-ray source with the *ASCA* and *ROSAT* satellites. We report here the detection of circularly polarized continuum emission from IRS 5 at centimeter wavelengths. Already known to be a highly variable radio source, the polarization fraction is seen to range from $V/I \simeq 10\%$ to $\simeq 37\%$ on a day timescale. This demonstrates that radio emission from protostars, previously attributed in most cases to ionized thermal outflows, can sometimes arise instead from nonthermal processes; *i.e.* gyrosynchrotron emission from particles accelerated *in situ* by magnetic reconnection flares. Together with the X-ray data and indications of MeV particles in the solar nebula obtained from meteoritic materials, it contributes to the growing evidence for high energy processes during the earliest stages of low mass star formation.

Subject headings: Infrared: Stars; ISM: Individual, Corona Australis Cloud; Radio Continuum: Stars; Solar System: Formation; Stars: Pre-Main-Sequence; X-Rays: Stars

1. Introduction

X-ray and radio continuum studies have established that high levels of magnetic activity are characteristic of various stages of low mass early stellar evolution. *Einstein* and *ROSAT* images of nearby star forming regions show hundreds of X-ray luminous T Tauri stars with flaring and spectral properties similar to those seen in magnetically active late-type stars such as RS CVn systems (e.g. Feigelson & DeCampli 1981 and review by Montmerle et al. 1993). These include both classical T Tauri (CTT) stars exhibiting strong star-disk interactions and weak-lined T Tauri (WTT) stars with little or no circumstellar disks. Several dozen WTT stars have also been detected at centimeter-band radio continuum wavelengths (e.g. Feigelson & Montmerle 1985 and review by André 1996). VLBI measurements of the brighter sources indicate that the emitting region arises from the star or inner disk and not from an extended thermal wind or jet. Circular polarization has been detected in a few cases, directly demonstrating that the emission process is solar-type gyrosynchrotron emission (e.g. White, Pallavicini & Kundu 1992). No radio flares have been confidently seen in CTT stars, but this absence can be attributed to free-free absorption in the partially ionized winds around these stars (André 1996).

More recently, X-ray flaring has also been observed in heavily obscured young stellar objects. Using the classification scheme based on infrared spectral energy distributions (Lada 1987; André & Montmerle 1994), these are mostly Class I objects which are best modeled as accreting protostars with ages around 10^5 yr (Adams, Lada & Shu 1987). *ASCA* and *ROSAT* studies of the Corona Australis cloud core have revealed a cluster of X-ray emitting Class I objects, one of which exhibited a rapid flare with an unusually hard X-ray spectrum (Koyama et al. 1996; Neuhäuser & Prebisch 1997). X-rays have also been detected from protostars in Ophiuchi and NGC 1333 cloud cores, including an extremely powerful flare from YLW15 (Grosso et al. 1997; Preibisch 1997; Kamata et al. 1997).

Note that X-rays have been sought but not detected from numerous other Class I sources, suggesting that high levels of magnetic activity in protostars are not ubiquitous or have short duty cycles (Carkner et al. 1997).

We report here the detection of circular polarization from a Class I T Tauri star, IRS 5 in the Corona Australis 'Coronet Cluster'. One previous case of circular polarization from a possible protostar has been reported, T Tau South (Phillips, Lonsdale & Feigelson 1993; Skinner & Brown 1994). This emission has been resolved with MERLIN as two lobes of opposite helicity separated by $0.1''$, suggesting particle acceleration in the bipolar outflow (Ray et al. 1997). But it is unclear whether infrared companions like T Tau S are in their initial infall phase or are more mature T Tauri stars experiencing an episode of accretion (Koresko, Herbst & Leinert 1997). Our direct demonstration of relativistic particles in a protostellar system may have important astrophysical implications. It contributes to the growing evidence for high energy processes during the earliest stages of stellar evolution, and supports meteoritic evidence for the bombardment of solar nebula solids by MeV particles (Feigelson 1997 and §4 below).

2. The Coronet Cluster and IRS 5

To optimize the chances of detecting nonthermal radio emission from a Class I object, we observed the 'Coronet Cluster' of infrared sources in the Corona Australis core at a distance of 130 pc (Taylor & Storey 1984). The molecular core is $11' \times 20'$ (0.4×0.7 pc) in size with about 50 $M_\odot$ of molecular gas (Harju et al. 1993). A detailed study of the pre-main sequence stellar population in JHK and other bands by Wilking et al. (1997, henceforth W97) reveals 27 likely members including three optically bright intermediate mass stars with Class IIID infrared spectra, 5-6 Class I objects (IRS 1 = HH100-IR, IRS 2, IRS 3, IRS 5, IRS 9 and possibly T CrA), and one Class 0 source (IRS 7; Saraceno et al.

1996). CTTs and WTTs comprise the remainder of the population, including five brown dwarf candidates. Several Herbig-Haro objects and molecular flows are present, though the association of outflows with specific stars is sometimes unclear (W97; Anderson et al. 1997). Most relevant to our study is the discovery of hard X-ray emission from several young stellar objects within the central $\sim 4'$ region including $3-5$ of the protostars (IRS 1, IRS 2, IRS 5 and possibly IRS 7 and IRS 9; Koyama et al. 1996; Neuhäuser & Preibisch 1997) demonstrating that magnetically confined hot plasma is present in these systems.

Radio continuum maps of the Corona Australis core region were first made with the NRAO Very Large Array [1] (VLA) by Brown (1987). Twelve sources were detected, most in the range $0.2-2$ mJy at 6cm and 2cm. The Class 0 object IRS 7 coincides with the brightest radio source, Brown 10W with $\simeq 5$ mJy (W97). Four other radio sources have young stellar counterparts including the Class I sources IRS 1 and IRS 5. Suters et al. (1996) monitored the region over several years using the VLA and Australia Telescope Compact Array. IRS 5 showed a flare of 6.6 mJy in 1992 compared to its usual levels around $0.6-1.5$ mJy at 6 cm. Circular polarization was sought but not detected during the VLA observations; unfortunately, polarization measurements were not made during the flare event. From the flat spectrum and absence of polarization, Suters et al. concluded that the emission process in IRS 5 is thermal and that it experienced an outburst in mass loss. This interpretation was reasonable as thermal radio emission with jet-like morphologies are seen in a number of protostars at the base of Herbig-Haro and molecular outflows (Anglada 1996, Rodriguez 1997 and references therein).

IRS 5 has also been the subject of concentrated study at infrared wavelengths. A protostellar evolutionary stage is suggested from its Class I spectral energy distribution

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

(1.6 − 100 μm), quantified by its 2 − 20 μm spectral index, dlog(λF_λ)/dlogλ = 1.15 (Wilking et al. 1986). Strong 3.1 μm ice-band absorption (Chen & Graham 1993) and 600 mJy 1.3 mm continuum flux (Saraceno et al. 1996) are also characteristic of a deeply embedded, protostellar phase. But IRS 5 may be akin to the flat-spectrum sources and somewhat more evolved than Class I objects (Calvet et al. 1994). A patchy envelope gives rise to a near-infrared reflection nebula (Taylor & Storey 1984; Castelaz & Hackwell 1987) and an infrared spectrum shows veiled K-type photospheric absorption lines (Greene & Lada 1996). But the degree of veiling in flat-spectrum sources implies disk accretion rates significantly higher than T Tauri stars (Greene & Lada 1996). Hence we identify IRS 5 with a protostellar, or perhaps late protostellar, stage of evolution. We note that IRS 5 is reported to be double at 1.6 μm and 2.2 μm with a component separation of 0.6″ (Chen & Graham 1993). High resolution observations which resolve the individual components are needed to confirm the binarity and measure the relative contributions of each component to the composite spectrum.

3. Observations and results

Observations of the Corona Australis cloud core were made on 19 and 20 January 1997 with the VLA in a hybrid BnA configuration in the 3.5 cm X band (8.4 GHz). Twenty-six antennas were available, each with primary beamwidth about 5.3′. A total of 7.2 hours over 10 hours were spent pointed at $19^h01^m51^s$ $-36°57′39″$ (J2000), near the center of the cluster. Observations were made in spectral line mode with 8 channels of 3.125 MHz width in each of two IFs for a total effective bandwidth of 44 MHz. This mode reduces bandwidth smearing far from the pointing center. The local phase calibrator 1744-312 was observed every 15 minutes, and flux densities were calibrated to 3C286. The weather was clear on 19 January but 20 January suffered heavy clouds with up to 10 mph winds. Clouds and wind, coupled with the low elevation of the target ($3-5$ airmasses) produced rapidly variable phases across the array. For some time intervals and antennas, the observations of 1744-312 were not sufficiently frequent to permit tracking of antenna phases. Some but not all of the unstable data could be removed from the analysis. Data analysis was accomplished with the spectral line calibration and mapping programs within NRAO's Astronomical Image Processing System. Large maps covering $6.8' \times 6.8'$ with $0.60'' \times 0.25''$ synthesized beamwidths were constructed and CLEANed for different time intervals. Self-calibration could not be applied because sources in the field are too weak. The root-mean-square noise (RMS) level in the total intensity I and circular polarized V maps for the entire dataset is 16μJy.

The total intensity maps (not shown) are similar to those shown in Brown (1987) and Suters et al. (1996), though at higher resolution. Eight isolated sources are found using a $5 \times RMS$ existence criterion which include all six sources found by Brown in our field of view and two additional fainter sources. Table 1 gives the source positions, I and V flux densities, counterparts from the VLA study of Brown (1987), X-ray study of Koyama et al. (1996) and infrared study of W97. The source positions are accurate to about $\pm 1''$, considerably below the usual accuracy of the VLA due to the phase instabilities. The reported flux densities are measured over a $2'' \times 2''$ region centered on each source, and upper limits represent the highest pixel in this region. Corrections for primary beam attenuation have been applied. I and V flux densities for the calibrator 1744-312 are included for comparison.

The principal result indicated in Table 1 is the presence of circular polarization from source 3 which is associated with the Class I source IRS 5. The statistical significance of the result is very high: $V = 222 \pm 16$ μJy ($14 \times RMS$) or $V/I = 17 \pm 1\%$ in the CLEAN map for the entire dataset. The peak V flux density, which is degraded by phase errors, is $7 \times RMS$.

The emission is present at all times during the observations and appears to range from 0.15 to 0.45 mJy. The total intensity I is also variable with average flux density 1.9 mJy ($V/I \simeq 10\%$) on 19 January and 0.8 mJy ($V/I \simeq 37\%$) on 20 January. Note that due to the uncorrected phase errors, all eight sources in Table appear to vary by $\pm 20 - 50\%$ ($\pm 10\%$ for the brightest source 7). But it is virtually impossible for uncorrected atmospheric phase noise to create a spurious strong V signal at a localized region of a map. The three stronger sources in the field all show no V emission ($V/I < 2\%$, $3 \times RMS$) and the calibrator has $V/I < 0.04\%$. A VLA instrumental effect known as beam squint can induce false circular polarization signals for off-axis sources. But it would have produced a stronger V flux for sources 7 and 8, and in any case cannot account for more than $V/I \simeq 1.5\%$ or $\sim 10\%$ of the V emission seen from IRS 5 (Vourlidas & Bastian 1993).

4. Discussion

We find that the embedded Corona Australis young stellar object IRS 5 is emitting circularly polarized centimeter continuum radiation. Except for earlier reports concerning T Tau S (§1), this is the first such finding for a pre-main sequence star in the protostellar phase of evolution. The only realistic mechanism for producing this polarization is gyrosynchrotron by $T > 10^8$ K thermal or trans-relativistic nonthermal electrons gyrating in magnetic fields (Dulk 1985). Explosive magnetic field reconnection is the only viable way to heat or accelerate electrons to these levels, and further accounts for the radio variability on timescales of a day or less. The field configurations must have large-scale organization, as emission from tangled field geometries would cancel out the net circular polarization.

Our finding thus provides direct astronomical evidence for both large-scale fields, magnetic reconnection events and energetic ($\sim$MeV) electrons in protostellar systems. It supports and extends indications of protostellar magnetic flaring recently acquired from X-ray measurements (§1). Quantitatively, IRS 5 has radio and X-ray luminosities $L_R \simeq 2.8 \times 10^{16}$ erg s^{-1} Hz^{-1} (Table 1 assuming $d = 130$ pc) and $L_x \simeq 3 - 5 \times 10^{30}$ erg s^{-1} (Koyama et al. 1996; Neuhäuser & Prebisch 1997), placing it near the $L_r - L_x$ relationship established for late-type magnetically active stars (Figure 1). Other protostars detected in both bands also have similar $L_r - L_x$ values. Nonthermal magnetic activity in low-mass stars may thus persist from the Class I protostellar phase of evolution through the main sequence without change in fundamental physics.

As with X-ray studies, however, we do not know the origins and structure of these fields. We cannot discriminate between fields with both footprints rooted in the stellar photosphere, with one footprint in the star and the other near the disk corotation radius, both footprints in the disk, open field lines in an outflow above the disk, or field lines connecting close companion stars (e.g. Feigelson et al. 1994). We also do not know whether these are 'fossil' fields inherited from the molecular cloud or fields generated by dynamos in the protostar or disk (André 1996). It is certainly tempting to attribute the emission to large-scale fields connecting the star and disk, as several independent lines of argument suggest that such fields are responsible for the loss of stellar angular momentum and the generation of winds in young stellar objects (e.g. Edwards et al. 1993; Shu et al. 1994). The reconnection producing the X-ray and radio flares may arise from fluctuating departures from corotation between the star and disk (Shu et al. 1997).

We also must confront the mystery why other protostars which appear to be thermal emitters have virtually the same radio luminosities as IRS 5 and other nonthermal young stars (Figure 1 and André 1996). Elongated morphologies on scales of $10^1 - 10^3$ AU are seen in about 20 protostellar sources, with structures, spectra and proper motions consistent with models of ionized collimated outflows (Anglada 1996, Rodriguez 1997, and references therein). IRS 1, IRS 7 and IRS 2 in CrA may be examples of such thermal protostellar radio sources. One possible explanation is that many protostars undergo nonthermal flaring, but the emission is free-free absorbed during outflow phases. While the gaseous environment of IRS 5 is complex (W97), it is possible that its outflow activity is currently in quiescence. As most previous VLA studies have concentrated on YSOs producing large-scale Herbig-Haro or molecular outflows and have not been sufficiently sensitive to detect V emission (L. Rodriguez, private communication), it is plausible that nonthermal radio emission from other protostars has been missed. Brown (1987) and Suters et al. (1996), for example, did not detect the IRS 5 V flux due to limited sensitivity or inappropriate instrumental configuration.

Finally, we note that our demonstration that energetic particles are generated in protostellar magnetic flares may have profound implications for our understanding of the solar nebula. While the evidence is often complex and subject to different interpretations, many puzzling properties of pristine meteorites can be attributed to the bombardment of solids by MeV protons or other particles. These include the presence of short-lived nucleides and other isotopic anomalies in Ca-Al-rich inclusions, and excess spallogenic ^{21}Ne and particle tracks in some meteoritic grains (e.g. Fowler, Greenstein & Hoyle 1962; Clayton, Dwek & Woosley 1977; Feigelson 1982; Woolum & Hohenberg 1993; Feigelson 1997; Lee et al. 1997). CrA IRS 5 may provide an important astronomical analogue of particle acceleration in the early solar system.

We are very grateful to Michael Rupen (NRAO) for his expert help in arranging and analyzing this dataset. We appreciate helpful discussions with Philippe André, Alex Brown and Luis Rodriguez on YSO radio emission, and with Charles Lada, Michael Meyer and Tom Greene on the nature of IRS 5. This study was partially supported by NASA contract NAS8-38252 (Penn State) and NSF RUI grant AST-9417210 (Missouri - St. Louis).

REFERENCES

Adams, F., Lada, C. & Shu, F. 1987, ApJ, 312, 788

Anderson, I. M., Harju, J., Knee, L. B. & Haikala, L. K. 1997, A&A, 321, 575

André, P. 1996, in *Radio Emission from the Stars and the Sun*, ed. A. R. Taylor & J. M. Paredes (San Francisco:ASP), p. 273

André, P. & Montmerle, M. 1994, ApJ, 420, 837

Anglada, G., 1996. 1996, in *Radio Emission from the Stars and the Sun*, ed. A. R. Taylor & J. M. Paredes (San Francisco:ASP), p. 3

Benz, A. O. & Güdel, M. 1994, A&A, 285, 621

Brown, A. 1987, ApJ, 322, L31

Calvet, N., Hartmann, L., Kenyon, S. J. & Whitney, B. A., 1994, ApJ, 434, 330

Carkner, L., Mamajek. E., Feigelson, E., Neuhäuser, R., Wichmann, R. & Krautter, J. 1997, ApJ, in press

Carkner, L., Kozak, J., & Feigelson, E. D. 1997, in preparation

Castelaz, M. W. & Hackwell, J. A. 1987, ApJ, 314, 317

Chen, W. P. & Graham, J. A. 1993, ApJ, 409, 319

Chiang, E., Phillips, R. B. & Lonsdale, C. J. 1996, AJ, 111, 355

Clayton, D., Dwek, E. & Woosley, S. 1977, ApJ, 214, 300

Dulk, G. A. 1985, ARAA, 23, 169

Edwards, S., Strom, S. E., Herbst, W., Attridge, J., Merrill, K. M., Probst, R. & Gatley, I. 1993, AJ, 106, 372

Feigelson, E. D. & DeCampli, W. M. 1981, ApJ, 243, L89

Feigelson, E. D. 1982, Icarus, 51, 155

Feigelson, E. D. & Montmerle, T. 1985, ApJ, 289, L19

Feigelson, E. D., Welty, A. D., Imhoff, C. L., Hall, J. C., Etzel, P. B., Phillips, R. B. and Lonsdale, C. J. 1994, ApJ, 432, 373

Feigelson, E. D. 1997, in Mem. Ital. Astr. Soc., in press

Fowler, W., Greenstein, J. & Hoyle, F. 1962, Geophys. J. RAS, 6, 148

Greene, T. P. & Lada, C. J. 1996, AJ 112, 2184

Grosso, N., Montmerle, T., Feigelson, E. D., André, P., Casanova, S. & Gregorio-Hetem, J., 1997, Nature, 387, 56

Harju, J., Haikala, L. K., Mattila, K., Mauersberger, R., Booth, R. S. & Nordh, H. L. 1993, A&A, 278, 569

Kamata, Y., Koyama, K., Maeda, Y., Ozaki, M., Tawara, Y., Ueno, S. & Yamauchi, S. 1997, PASJ, in press

Koresko, C. D., Herbst, T. M. & Leinert, Ch. 1997, ApJ 480, 741

Koyama, K., Ueno, S., Kobayashi, N. & Feigelson, E. 1996, PASJ, 48, 87

Lada, C. J. 1987, in *Star Forming Regions*, ed. M. Peimbert & J. Jugaku (Dordrecht:Kluwer), p. 1

Lee, T., Shu, F. H., Shang, H. & Glassgold, A. E. 1997, in preparation

Leous, J. A., Feigelson, E. D., André, P. & Montmerle, T. 1991, ApJ, 379, 683

Montmerle, T., Feigelson, E. D., Bouvier, J. & André, P. 1993, in *Protostars and Protoplanets III*, ed. E. Levy & J. Lunine (Tucson:Arizona), p. 689

Neuhäuser, R. & Preibisch, T. 1997, A&A, 322, 37

Phillips, R. B., Lonsdale, C. J. & Feigelson, E. D. 1993, ApJ, 403, L43

Preibisch, T. 1997, A&A, 324, 690

Ray, T. P., Muxlow, T. W., Axon, D. J., Brown, A., Corcoran, D., Dyson, J. & Mundt, R. 1997, Nature, 385, 415

Rodriguez, L. F. 1997, in *Herbig-Haro Flows and the Birth of Low Mass Stars*, eds. B. Reipurth & C. Bertout (Dordrecht:Kluwer), p. 83

Saraceno, P., André, P., Ceccarelli, C., Griffin, M. & Molinari, S. 1996, A&A, 309, 827

Shu, F., Najita, J., Ostriker, E., Wilkin, F., Ruden, S. & Lizano, S. 1994, ApJ, 429, 781

Shu, F. H., Shang, H., Glassgold, A. E. & Lee, T. 1997, Science, 277, 1475

Skinner, S. L. & Brown, A. 1994, AJ, 107, 1461

Suters, M., Stewart, R. T., Brown, A. & Zealey, W. 1996, AJ, 111, 320

Taylor, K. N. & Storey, J. W. 1984, MNRAS, 209, 5P

Vourlidas, A. & Bastian, T. 1993, VLA Test Memo #180, NRAO

Wilking, B. A., McCaughrean, M. J., Burton, M. G., Giblin, T., Rayner, J., T. & Zinnecker, H. 1997, AJ, in press (W97)

Wilking, B. A., Taylor, K. N. & Storey, J. W. 1986, AJ, 92, 103

Woolum, D. S. & Hohenberg, C. 1993, in *Protostars and Planets III*, eds. E. H. Levy & J. I. Lunine, p. 903

This manuscript was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— Radio luminosity (in erg s^{-1} Hz^{-1}) vs. X-ray luminosity (in erg s^{-1}). The filled circle is CrA IRS 5 (Koyama et al. 1996; this paper), open circles are other protostars (Koyama et al.; Kamata et al. 1997; Grosso et al. 1997; Leous et al. 1991; this paper), and $\times$'s are weak-lined T Tauri stars in the Taurus-Auriga region (Chiang et al. 1996; Carkner et al. 1997). The line represents the empirical X-ray/radio relationship for active late-type stars (Benz & Güdel 1994). Note that this plot includes only those stars that have been detected in both X-rays and radio waves (many nondetections are omitted), and that observations were made at various wavelengths with *ROSAT*, *ASCA* and the VLA.

Table 1: Radio continuum sources in Corona Australis cloud core

Source	R.A. (J2000)	Decl.	I	V	Counterparts		
	h m s	$\circ$ $\prime$ $\prime\prime$	(mJy)	(mJy)	Radio[a]	X-ray[b]	Infrared[c] (Class)
1	19 01 41.6	−36 58 31	0.67	<0.10	...	4	IRS 2 (I)
2	19 01 43.3	−36 59 12	1.08	<0.07	5	...	Faint[d]
3	19 01 48.1	−36 57 21	1.36	0.23	7	5	IRS 5 (I)
4	19 01 50.7	−36 58 09	0.45	<0.06	8	6	IRS 1 (I)
5	19 01 53.7	−36 57 08	0.23	<0.06	...	...	R CrA[e] (Herbig Ae)
6	19 01 55.3	−36 57 16	1.58	<0.04	9	...	...
7	19 01 55.3	−36 57 22	3.74	<0.06	10W	8	IRS 7 (0)
8	19 01 56.4	−36 57 28	2.03	<0.05	10E	...	...
Cal[f]	...	...	473	<0.2	...	...	...

[a] From Brown (1987).

[b] From Koyama et al. (1996). Positions of X-ray sources 4, 5, and 6 are confirmed by Neuhäuser & Preibisch (1997).

[c] From W97 except IRS 7 (from Saraceno et al. 1996) and R CrA (from SIMBAD).

[d] Star with $K = 16.4$, $(H - K) = 1.45$. This is a brown dwarf if it lies in the CrA cloud and is $< 10^7$ years old (W97).

[e] = HBC 288 = IRAS 18585-3701. $V \simeq 10.0 - 13.6$ variable with A5e II spectral type. Radio source coincides with bright NW tip of optically bright nebula on digitized sky survey. Position in SIMBAD is inaccurate.

[f] VLA calibrator 1744-312