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A SEARCH FOR RADIO SOURCES NEAR DOUBLE HERBIG–HARO OBJECTS

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RESUMEN

Utilizando el *VLA* a 6-cm, llevamos a cabo una búsqueda de fuentes de radiocontinuo en la dirección de seis objetos Herbig-Haro *dobles*. Estos son objetos HH bien definidos, separados por unos pocos minutos de arco, que podrían estar siendo excitados por una misma fuente de energía. Encontramos un total de 17 fuentes de radiocontinuo en los campos estudiados. La mayoría de estas fuentes probablemente son objetos extragalácticos. Sólo en el caso de Reipurth 56-57 (=HH94-95) detectamos una fuente de radiocontinuo localizada entre ambos objetos HH. Se requiere de un estudio detallado en radio e IR para determinar la naturaleza de esta fuente.

ABSTRACT

Using the *VLA* at 6-cm we searched for radio continuum emission toward six *double* Herbig-Haro objects. These are well-defined HH objects separated by a few arcminutes that could be sharing a common exciting source. We detected a total of 17 sources in the fields mapped. Most of these sources are probably extragalactic objects. Only in the case of Reipurth 56-57 (= HH94-95) we detected a radio continuum source located between both HH objects. A detailed radio and IR study of this region is required to determine the nature of this radio source.

Key words: **HERBIG-HARO OBJECTS – INFRARED-SOURCES – NEBULAE-INDIVIDUAL – RADIO SOURCES-GENERAL – STARS-PRE-MAIN-SEQUENCE**

I. INTRODUCTION

Herbig-Haro objects are believed to be shocks excited by the collimated winds of young stars. These stars are often associated with far-infrared sources, bipolar molecular flows (Snell, Loren and Plambeck 1980, Rodríguez, Ho and Moran 1980), radio continuum emission (e.g., Cohen, Bieging and Schwartz 1982; Pravdo *et al.* 1985; Rodríguez *et al.* 1989, 1990), and jet-like nebulosities (e.g., Mundt and Fried 1983). These very young stars are often heavily obscured by their surroundings and this makes it difficult to identify them at optical and infrared wavelengths (e.g., Adams and Shu 1986). Indeed, the extinction can be sufficient to render the stars undetectable even in the near infrared wavelengths.

Most of the exciting sources of Herbig-Haro objects have been detected primarily at the IR or optical wavelengths, and after that at radio frequencies (e.g., L1551 IRS5, R Mon, SVS 13, T Tau, and HH24-IRS; see compilation by Curiel *et al.* 1989). The only case in which the exciting source has been detected first in the radio is the HH1-2 system, where Pravdo *et al.* (1985) detected emission from the exciting source (*VLA*1) and from the HH objects themselves. This case opens the possibility to detect and to study, in the radio wavelengths, the nature of the exciting source of HH systems where an IR or optical source has not been found and, furthermore, to detect and to study the HH objects themselves (see Rodríguez *et al.* 1990 for a detailed multifrequency and multiconfiguration *VLA* study of the HH1-2 system).

Elongated radio sources have been found for outflow systems like L1551 IRS5 (Bieging, Cohen and Schwartz 1984) and HH1-2 *VLA*1 (Rodríguez *et al.* 1990). Likewise, Brown (1987) reported the detection of a radio source at the center of the HH99-101 (R CrA) region that consists of two compact sources with two jets of radio emission extending in a roughly orthogonal fashion to the line joining the compact sources. This is the same morphology found in the radio source associated with L1551 IRS5 by Rodríguez *et al.* (1986), and interpreted by them as evidence for circumstellar ($\sim$ 25 AU) collimation. In the case of the R Cr A source, however, the dimensions are about 50 times larger than in the L1551 IRS5 source. The detection of more central radio sources of outflow systems is very important since their size and morphology provide information on the scale and characteristics of the collimation.

In this paper we present *VLA* observations at 6-cm of six *double* HH objects selected from the literature in an attempt to detect their exciting sources in the radio wavelengths. These double HH objects are well-defined HH objects separated by a few arcmin, that could be

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TABLE 1

OBSERVED REGIONS

Source	Center of Field α (1950)	δ	Phase Calibrator	5-σ Upper Limit[a] (mJy per beam)
HH33-40	$05^h32^m53.0^s$	−06°19'56"	0539-057	0.4
Haro 3a-4a	05 33 35.7	−05 05 36	0539-057	0.7
HH38-43	05 35 51.0	−07 12 11	0539-057	0.4
Re 56-57	05 41 09.1	−02 36 28	0539-057	0.4
Th28	16 05 08.3	−38 55 16	1622-297	0.6
HH56-57	16 28 55.5	−44 48 57	1622-297	0.6

a. These upper limits apply to the HH objects in the region.

TABLE 2

6-CM SOURCES IN THE OBSERVED REGIONS

Field	Source	α (1950)[a]	δ	Peak Flux Density[b] (mJy per beam)
HH33-40	1	$05^h32^m48.3^s$	−06°18'14"	0.8
...	2	05 33 15.5	−06 24 54	5.0
Haro 3a-4a	1	05 33 28.0	−05 06 14	1.06
...	2	05 33 29.2	−04 56 43	17.9
...	3	05 33 30.7	−04 57 28	30.4
...	4	05 33 33.6	−04 58 15	23.7
HH38-43	1	05 35 42.2	−07 12 51	0.6
Re 56-57	1	05 41 08.3	−02 36 26	0.5
...	2	05 41 26.9	−02 36 10	1.4
Th28	1	16 05 09.8	−38 54 59	0.7
...	2	16 05 12.2	−38 50 48	1.4
...	3	16 05 12.4	−38 52 12	16.0
...	4	16 05 26.2	−38 53 27	3.6
HH56-57	1	16 28 27.0	−44 47 20	4.3
...	2	16 28 53.4	−44 51 50	1.7
...	3	16 29 06.7	−44 44 20	2.0
...	4	16 29 21.2	−44 43 31	3.3

a. Position of peak emission. Estimated error is 3".
b. Corrected for primary beam response.

sharing a common exciting source as in the case of HH 1-2. It is unclear, however, if these double HH objects share a common exciting source or if they are two independent systems.

II. OBSERVATIONS

The observations were made during 1988 August 26 with the Very Large Array (*VLA*) of the National Radio Astronomy Observatory[4]. The array was in the D configuration, providing an angular resolution of ∿ 10" at 6 cm. The data were reduced using the standard *VLA* calibration, mapping, and cleaning routines. The regions observed as well as the phase calibrators are given in Table 1. The absolute amplitude calibrator was 3C286. Maps of 12.8' X 12.8' with uniform weight were made to identify sources in the field. In the case of Haro 3a-4a, a map of 25.6' X 25.6' was made also in order to identify a bright source on the upper edge of the smaller (12.8' X 12.8') map. The positions and peak fluxes of the sources detected are given in Table 2. The peak fluxes have been corrected for the primary beam response. To be included as a detection, the peak flux must be at least five times the estimated rms noise determined from a blank region

4. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

near the center of the field. A total of 17 radio continuum sources have been detected in the six fields observed. In order to identify how many of these sources are associated with the molecular clouds, a search for IRAS point sources in the observed fields was made. Likewise, the positions of some of the stars that appeared to be close to radio sources were measured in the Palomar Sky Survey prints using a Mann measuring engine, obtaining a typical precision of $\sim$ 1.5 arcsec. We did not detect radio emission from the HH objects. The upper limits for their fluxes are given in Table 1.

III. COMMENTS ON INDIVIDUAL SOURCES

A total of 17 radio sources have been detected within the six fields observed. Following the formulation given by Rodríguez *et al.* (1989), the expected number of background radio sources at 6-cm with a flux equal or greater than 0.4 mJy within a *VLA* primary beam is about 3 sources per field, which gives an expected total of 18 sources in all the fields. Since 17 sources were detected, above a 5-σ level in the range of 0.4-0.7 mJy (see Tables 1 and 2), we believe that most of them are background objects. Nevertheless, as discussed below, some of the sources may be associated with the molecular clouds.

None of the sources is located in the immediate vicinity ($\sim$ 10″) of the Herbig-Haro objects. Also, there is no association between the detected radio sources and IRAS point sources (1985) or H_2O masers (Cesaroni *et al.* 1988). Brief comments on individual regions are given below.

a) *HH33–40*

We detected 2 radio sources in this region. None of the radio sources coincides spacially with the HH objects or with an IRAS source (within 10″). The strongest radio source in this region (source 2 in Table 2) seems to be related to an arc-like filamentary structure, at the south-east of HH 33–40, which extends toward HH34 (see Figure 1 of Reipurth and Sandell 1985). The streamer shows an HH-like spectrum with moderately high excitation and low electron density (Cohen and Schwartz 1983; Reipurth and Sandell 1985). This radio source is located to the south-east of a T Tauri star, V571 Ori, and within 6″ from a bright emission region in the arc-like structure (region 22 in Strom *et al.* 1986). This radio source has been also detected and studied in detail by Yusef-Zadeh *et al.* (1989), who interpret it as a non-thermal radio emitting pre-main-sequence star responsible for driving the large optical structures.

b) *Haro 3a–4a*

Two sources in this region are of some interest. One is about 28″ to the east of the variable emission-line AR Ori (e.g., Reipurth 1985). The other is a triple source about 8′ to the north of the HH objects. These sources are extended, and with the morphological appearance of H II regions. There is an optical stellar object almost at the center between the two brightest components. The position measured for this star is $\alpha(1950) = 05^h33^m 31.9^s$, $\delta(1950) = -04°57'55''$.

c) *HH38–43*

We detected one radio source in this field. This source does not coincide spatially with the HH objects or with IRAS sources.

d) *Reipurth 56–57 (= HH94–95)*

These two very faint objects were proposed as HH objects by Reipurth (1985), after a survey of the L1641 and L1630 dark clouds in Orion. They have recently being confirmed as *bona fide* HH objects, receiving the numbers 94 and 95 (Reipurth 1989). As in the other fields, we did not detect emission from the HH objects. However, we found a radio continuum source (source 1 in Table 2) located near the geometric center of this HH system (Figure 1). The same morphology was found by Pravdo *et al.* (1985) in the HH1-2 system. The similarity with the HH1-2 system makes the radio continuum source 1 a good candidate for the exciting source of these HH objects. A detailed study of this region at different radio and infrared frequencies is required in order to confirm the possible association between this radio source and the HH objects.

Source 2 in Table 2 is also an interesting source since it is located 12″ away from a star. The position measured for this star is $\alpha(1950) = 05^h41^m26.3^s$, $\delta(1950) = -02° 36'26''$.

e) *Th28*

Th28 is a T Tauri like star with a string of Herbig-Haro objects, located in the Lupus T-association. Three Herbig-Haro objects (HHE1, HHE2 and HHW) are located on both sides of the star, about 30″ and 87″ east and 38″ west, respectively (Krautter 1986; Graham and Heyer 1989). A proper motion of 0.5″ yr^{-1} for HHE1, which corresponds to a tangential velocity of 316 km s^{-1}, was found by Krautter (1986). One of the four radio sources detected in this region (source 1 in Table 2) is located $\sim$ 24″ to the north-east of the position of Th28. This angular separtion rules out a direct association. From the figure given by Krautter (1986), we estimate a separation of about 20″ between this radio source and HHE1.

f) *HH 56–57*

Four radio sources were detected in this field. None of them seems to be related with the HH objects. Likewise, there is no spatial relation between the radio sources and IRAS sources or optical objects.

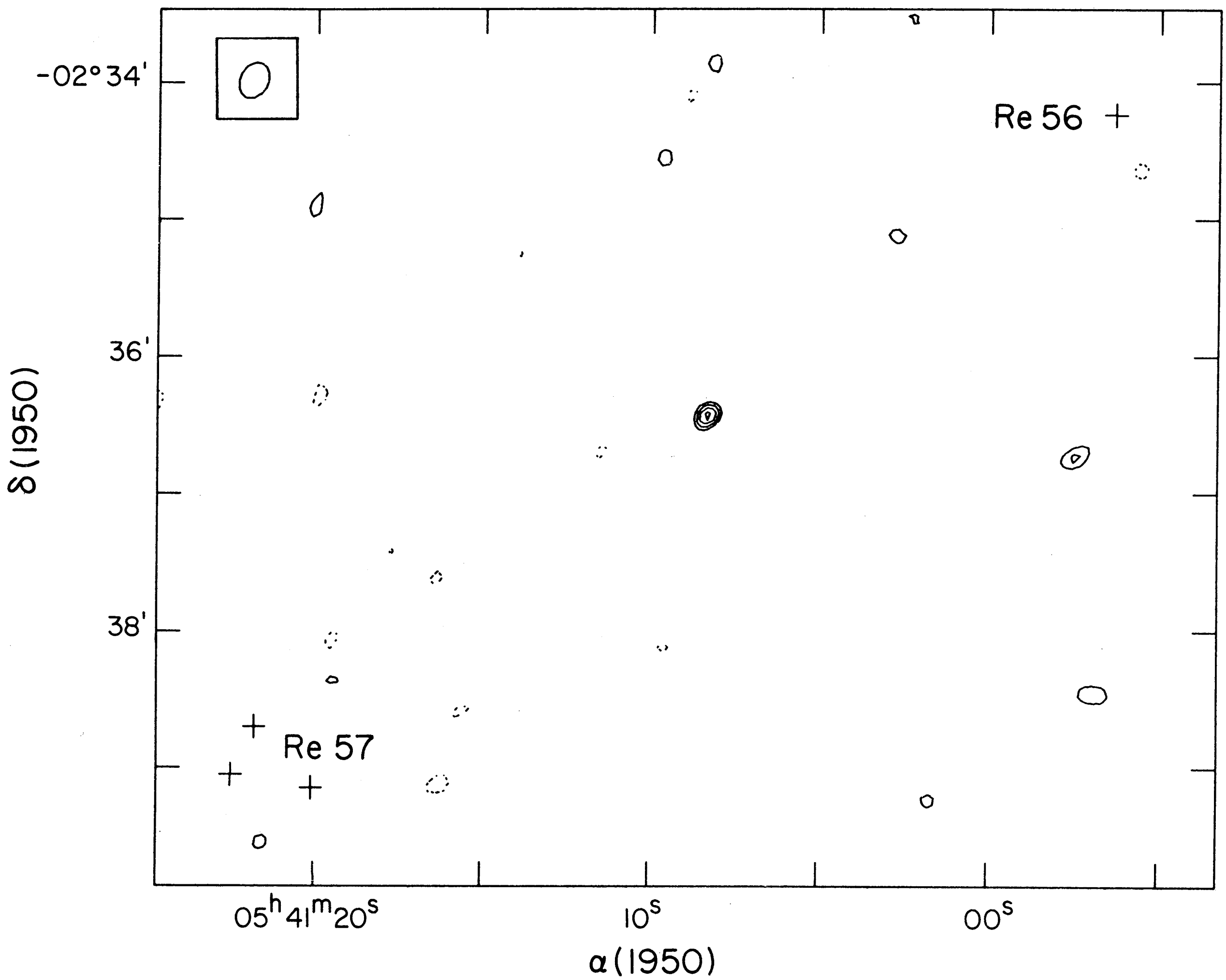

Fig. 1. Uniform-weight, 6-cm *VLA* map of the Reipurth 56–57 (= HH94–95) region. The crosses mark the position of the HH objects. The radio object at the center could be associated with the exciting source of the system. The beam is shown in the top left of the figure. Contours are −3, 3, 4 5, and 6 times the 1-σ rms value of 80 μJy per beam.

IV. CONCLUSIONS

We searched for radio continuum emission toward six double HH objects. Seventeen radio continuum sources were detected in six fields. Most of them seem to be background objects. None of the radio sources seems to be associated with Herbig-Haro objects or with IRAS sources. One of the 17 radio sources is in the proximity of an optical object (within 6 arcsec), while other four are within 30 arcsec from optical objects.

The most promising source in the six fields studied is a source located between the HH objects Reipurth 56 and 57 (source 1 in Table 2). The proximity of this source to the center of symmetry of the two HH objects is reminiscent of the geometry of the HH 1-2 system, but in this case, the angular scale of the Reipurth 56–57 system is considerably larger (about three times). A detailed radio and IR study of this region is required to test if this radio object is the exciting source of the Reipurth 56–57 system or a background source unrelated to the cloud.

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