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DETECTION OF RADIO CONTINUUM EMISSION FROM THE HERBIG-HARO OBJECTS 80 AND 81 AND THEIR SUSPECTED ENERGY SOURCE

L.F. Rodríguez[1]

Instituto de Astronomía
Universidad Nacional Autónoma de México

and

B. Reipurth

European Southern Observatory
Santiago, Chile

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RESUMEN

Reportamos la detección, hecha con el *VLA* a 6-cm, de radio continuo proveniente de los objetos Herbig-Haro 80 y 81. El flujo de estos objetos HH es similar al observado en HH1 y 2, pero su luminosidad en radio es ∿ 10 veces mayor, puesto que estos objetos están a 1.7 kpc, mientras que HH1 y 2 están a 0.46 kpc. También detectamos emisión de la fuente IRAS 18162-2048, que se cree es la fuente excitadora del sistema. La emisión proveniente de esta fuente tiene morfología alargada y apunta aproximadamente a HH80-81.

ABSTRACT

We report the 6-cm detection, made with the *VLA*, of the Herbig-Haro objects 80 and 81. The flux of these HH objects is similar to that observed in HH1 and 2, but their radio luminosity is intrinsically ∿ 10 times larger since these objects are at 1.7 kpc, while HH1 and 2 are at 0.46 kpc. We also detected ratio continuum emission from IRAS 18162-2048, the presumed exciting source of the system. The emission from this source is elongated and approximately points to HH80-81.

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

I. INTRODUCTION

The detection of radio continuum emission from the Herbig-Haro objects 1 and 2 and their central source of energy (Pravdo *et al.* 1985), and the subsequent detailed *VLA* study of the region (Rodríguez *et al.* 1989) have produced a significant advance in our understanding of the HH phenomenon. Among other results, it has been possible to identify the central source of energy of the system and to show that the angular size of the major axis of this source depends on frequency as $\theta_s \propto \nu^{-0.8}$, while the total flux goes as $S_\nu \propto \nu^{0.3}$, results that can be explained with a confined, thermal jet model (Reynolds 1986). It has also been possible to show that the radio emission from the HH objects themselves is optically-thin free-free, and as well as to estimate the shock parameters from these data (Curiel, Cantó, and Rodríguez 1987). Finally, the proper motions of the HH objects have been confirmed comparing the radio data with optical data taken a decade before.

The same techniques applied to HH1-2 and its central source of energy can, in principle, be applied to other HH-object plus source-of-energy systems. The radio measurements could be particularly valuable in the case of HH objects that are heavily or totally obscured at optical wavelengths. However, the fact that the Hα intensities (that are expected to be correlated with the radio continuum emission) of other known HH objects are about ten times weaker than HH1 and HH2 has impeded these studies. Indeed, the only well established radio detection of HH objects is for the case of HH1 and 2.

Recently, Reipurth and Graham (1988) reported several new HH objects in star forming regions. They found that two of these new HH objects, HH80 and 81 in Sagittarius, have complex velocities and high excitation conditions and are among the brightest known. A detailed, high resolution, spectroscopic study of HH80 and 81 has revealed velocity structure over the remarkable range of

1.Harvard-Smithsonian Center for Astrophysics.

TABLE 1

6-CM SOURCES IN THE HH80-81 REGION

Source	α (1950)[a]	δ	Total Flux Density[b] (mJy)	Identification
1	$18^h15^m57.0^s$	−20°53'52"	6.9	...
2	18 16 06.9	−20 53 09	1.1	HH80
3	18 16 07.5	−20 52 24	1.7	HH81
4	18 16 08.2	−20 53 48	0.8	...
5	18 16 13.0	−20 48 49	5.5	IRAS 18162-2048
6	18 16 14.1	−20 54 04	1.1	...

a. Position of peak emission. Estimated error is 2".
b. Corrected for primary beam response.

700 km s^{-1} (Heathcote and Reipurth 1989). Since these new HH objects appeared as ideal candidates for radio studies, we undertook *VLA* observations of them. These observations are described in §II. Our results and discussion are presented in §III and we summarize our conclusions in §IV.

II. OBSERVATIONS

We made continuum observations of the HH 80-81 region at 6-cm (1988 July 18) using the *Very Large Array* of NRAO[2] in the D configuration. The angular resolution was ∿ 10″. We chose to observe with the lowest angular resolution available at the *VLA* to optimize the possibility of detecting the sources, that were known to be extended (several arcsec) in the optical range (Reipurth and Graham 1988). The observations were made with an effective bandwidth of 100 MHz. The absolute amplitude calibrator was 3C286 and the phase calibrator was 1748-253. The data were edited and calibrated using standard *VLA* procedures.

III. RESULTS AND DISCUSSION

In Figure 1 we show a 6-cm, uniform-weight map of the HH80-81 region superposed on an Hα CCD image taken at the Danish 1.5-m telescope at ESO, La Silla. In Table 1 we give the positions and fluxes of the sources in the region. We detected both HH objects, each with flux density of ∿ 1 mJy. This flux is similar to that measured in HH1 and HH2 (Pravdo *et al.* 1985; Rodríguez *et al.* 1989). However, this source is at 1.7 kpc

2. NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

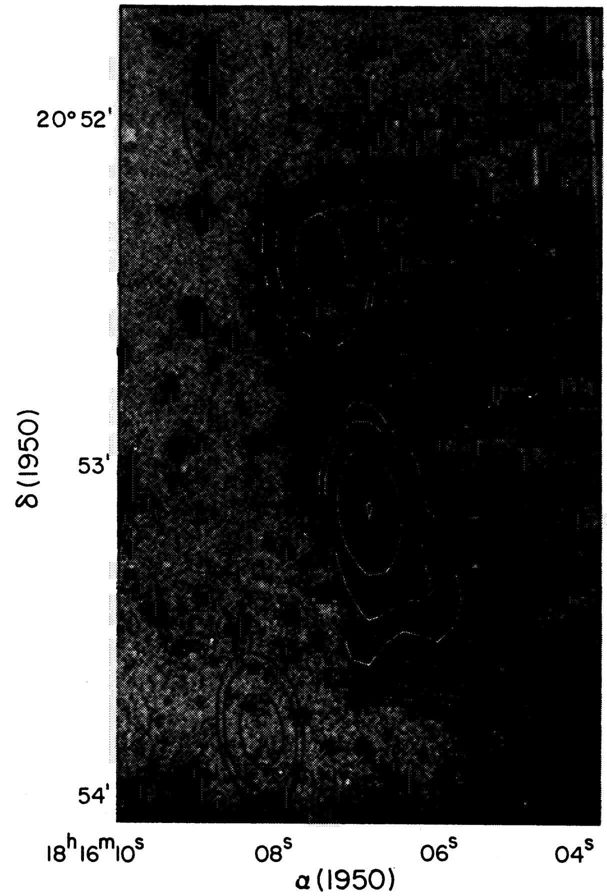

Fig. 1. Uniform weight, 6-cm *VLA* map of HH80 and HH81 superposed on an Hα CCD image. Contours are −3, 3, 5, 10, 20 and 30 times 50 μJy/beam. The half power contour of the beam is also shown.

(Rodríguez *et al.* 1980), while HH1-2 is at 460 pc (Herbig and Jones 1981). This makes HH80 and 81 about 10 times intrinsically more luminous in the radio than HH1 and 2.

Perhaps more interestingly, we also detected what appears to be the exciting source of the HH80-81 objects. Our map was centered on the HH objects, but we were able to map at 6-cm a field range enough to include IRAS 18162-2048, a luminous ($L_{IRAS} \sim 10^4\ L_\odot$) infrared source proposed by Reipurth and Graham (1988) as the exciting source of HH80-81. Remarkably, the source exhibits elongated morphology (see Figure 2) and its major axis points approximately to HH80-81. This geometry is similar to that found for the central sources of the L1551 (Bieging and Cohen 1985; Rodríguez *et al.* 1986) and HH1-2 (Rodríguez *et al.* 1989) systems; but in HH80-81 the angular size of the major axis of the radio source associated with the presumed exciting source is $\sim 2'$ ($\sim$ 1 pc), while in L1551 and HH1-2 it is only a few arcsec (of order 0.01 pc at the distances of these sources).

The source IRAS 18162-2048 has been studied previously by Rodríguez *et al.* (1980) since it is associated with the nebulosities GGD27 and 28 (Gyulbudaghian, Glushkov and Denisyuk 1978). These last authors, based on morphological arguments, proposed GGD27 and 28 as Herbig-Haro objects. Further spectroscopic studies showed, however, that they appear to be reflection nebulae surrounding visible stars (Hartigan and Lada 1985; Heathcote and Reipurth 1989). The region is clearly the site of recent star formation with detected water maser (Rodríguez *et al.* 1980), hot CO (Rodríguez *et al.* 1982), and ammonia (Torrelles *et al.* 1986) emission. Furthermore, Heathcote and Reipurth (1989) found several young stars in an optical study of the region around IRAS 18162-2048. There are also signs of molecular outflow (Rodríguez *et al.* 1982; de Vries *et al.* 1984), and Yamashita *et al.* (1989) report a bipolar outflow with blueshifted and redshifted lobes extending to the north and south, respectively. This morphology is consistent with that of the elongated radio source (see Figure 2) found in association with IRAS 18162-2048. Additionally, Yamashita *et al.* (1987) detected in the infrared a bipolar reflection nebula of similar extent and orientation as the radio source. Furthermore, Yamashita *et al.* (1989) also mapped a CS structure elongated east-west that could be the confining agent of this bipolar source. The radio continuum emission associated with IRAS 18162-2048 has been previously mapped by Rodríguez *et al.* (1980), Rodríguez and Cantó (1983), and Curiel *et al.* (1989). None of these observations had sufficient sensitivity to extended structures to detect the elongated morphology shown in Figure 2, and they most probably refer to the compact core of the source.

The source IRAS 18162-2048 was detected in the AFGL survey and in all four IRAS bands. Assuming that the source is at 1.7 kpc, its IRAS luminosity is $1.8 \times 10^4\ L_\odot$, corresponding to a B0 ZAMS star with an ionizing photon rate of $1.0 \times 10^{47}\ s^{-1}$ (Thompson 1984). If this ionizing photon rate would be used to produce an optically thin H II region, the region would be expected to have a 6-cm free-free flux density of $\sim$ 400 mJy. In contrast, the radio source associated with IRAS 18162-2048 has a total flux density of only 5.5 mJy (see Table 1). It is possible that our observations could be missing flux from a component more extended than $\sim 2'$, but this effect is unlikely to account for the large discrepancy. We believe that there is a real deficiency in the observed radio continuum emission. Several possibilities can account for this deficiency. The radio continuum emission could be optically thick in the cm range. However, the extended appearance of the source argues against this possibility. Two more likely explanations are that the dust is absorbing most of the *UV* photons or that the star has not yet reached the main sequence and is therefore cooler than a main sequence object of the same luminosity. A more speculative possibility is the following. Assume that the star *is not producing a significant flux of ionizing photons.* The association with a a molecular outflow, a high velocity H_2O maser, and the HH objects imply the presence of a powerful wind. This wind is, most probably, the energy source of the ionization observed in HH80 and 81. Can this wind be responsible also for the ionization observed in association with IRAS 18162-2048? We believe that this could well be the case. If we assume that the radio continuum emission

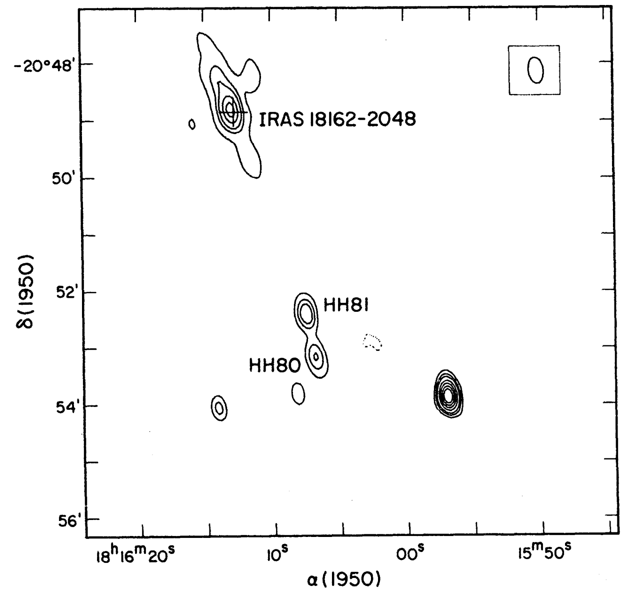

Fig. 2. Natural weight, *VLA* map at 6-cm of the HH80-81 and IRAS 18162-2048 region. This map was made with natural weighting to enhance the faint, extended structure associated with IRAS 18162-2048, the suspected exciting source of HH80 and 81. Contours are −1, 1, 2, 3, 5, 7, 9 and 11 times 400 μJy/beam.

associated with IRAS 18162-2048 is optically thin bremsstrahlung, an ionizing rate of $\sim 10^{45}$ s^{-1} is required. A similar rate is required to maintain HH80 and 81 ionized. From the formulation of Cox (1972) and Daltabuit and Cox (1972), we find that the shock-induced ionization rate from a stellar wind with mass loss rate $\dot{M}$ and terminal velocity v_∞ is approximately

$$N_S \simeq 5 \times 10^{45} \left[\frac{\dot{M}}{3 \times 10^{-7}\ M_\odot\ yr^{-1}}\right] \left[\frac{v_\infty}{1000\ \mathrm{km\ s^{-1}}}\right]^2 .$$

We can then account for all the observed ionization in the region (HH80 and 81 plus IRAS 18162-2048) with $\dot{M} \simeq 10^{-7}$ $M_\odot$ yr^{-1} and $v_\infty \simeq 1000$ km s^{-1}, values that appear reasonable for an early B-type star. Unfortunately, it is not possible at present to distinguish between a photoionized and a shock-ionized thermal radio source from its continuum alone (Curiel, Cantó and Rodríguez 1987). The distinction could possibly be made by observing radio recombination lines (McKee and Hollenbach 1987), but the sensitivity of presently available instruments is insufficient to detect the extremely weak lines expected.

We can also discuss briefly the energetics of the system, as compared to those of HH1-2. As noted above, HH80 and 81 are about 10 times more luminous than HH1 and 2. Furthermore, the projected separation between IRAS 18162-2048 and HH80-81 is $\sim 4'$ ($\sim$2 pc), while that between HH1 or HH2 and their exciting source VLA1 is $\sim$ 0.2 pc (Pravdo *et al.* 1985). Assuming equal collimation efficiency for both sources and that the mechanical power in the outflow scales linearly with the luminosity of the source, one concludes that IRAS 18162-2048 should be $\sim 10^3$ times more luminous than VLA1. This is not inconsistent with what is known of both regions since IRAS 18162-2048 has a luminosity of $\sim 10^4$ $L_\odot$, while VLA1 has a luminosity of $\sim$ 10 $L_\odot$ (Rodríguez, Roth and Tapia 1985).

Finally, we note that there are, in addition to HH80, HH81, and IRAS 18162-2048, three other radio continuum sources in the field (see Table 1 and Figure 2). These sources are probably extragalactic objects since they are not associated with any optical or infrared object and, for our sensitivity, 3-4 background sources are expected.

We are currently undertaking a detailed *VLA* study of the region with the following three purposes: 1) to establish the spectral index of HH80-81, its suspected source of energy, and the other sources in the field, 2) to study the morphology of these sources with an angular resolution 3 times better than our original observations, 3) to derive proper motions for the HH objects from radio multi-epoch observations, and 4) to search, at the northeast of IRAS 18162-2048, for the counterparts of HH80-81. This last possibility is quite interesting, since we could not detect in the optical any counterparts for HH80-81. If the morphology of this system is similar to that of HH1-2, counterparts are expected to exist, but are probably heavily obscured by the surrounding molecular cloud. Our presently available radio data cannot be used to search for these counterpart HH objects because the primary beam response at the expected position of the counterparts is negligible.

IV. CONCLUSIONS

Our main conclusions are:

1) We detected at 6-cm the Herbig-Haro objects 80 and 81. This is only the second (HH1-2 being the first) detection of radio continuum emission from HH objects. HH80 and 81 have fluxes comparable to HH1 and 2, but given their larger distance, are an order of magnitude intrinsically more luminous in the radio than HH1 and 2.

2) We also detected radio continuum emission associated with IRAS 18162-2048, the presumed exciting source of HH80 and 81. The radio source is elongated and points approximately to HH80 and 81. Its size ($\sim$ 1 pc) is two orders of magnitude larger than the elongated radio continuum sources associated with the energy sources of the L1551 and HH1-2 systems.

3) We propose that the ionization observed in IRAS 18162-2048 could be due, as is the case for HH80-81, to shocks.

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Bo Reipurth: European Southern Observatory, Casilla 19001, Santiago 19, Chile.
Luis F. Rodríguez: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., México.