THE ASTROPHYSICAL JOURNAL, 449:L127–L129, 1995 August 20

# VLA SPECTRAL LINE OBSERVATIONS OF A SHOCKED COLD H II REGION IN G70.7+1.2

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*Received 1995 April 12; accepted 1995 June 14*

## ABSTRACT

We have observed the molecular globule G70.7+1.2 at 1375 MHz using the C configuration of the VLA, and have imaged a peculiar H168$\alpha$ recombination line detected at the Arecibo radio telescope. The narrow width of the recombination line ($\Delta v \sim 3$ km s$^{-1}$) indicates gas cooler than 185 K and suggests that the globule harbors the coldest known H II region. Previous work showed that the recombination line came either from newly ionized gas outside a bow shock produced by supersonic motion of an early-type star through the molecular globule, or from a cold H II region inside the globule. The 20″ angular resolution of the VLA image of G70.7+1.2 was sufficient to resolve the separation between the nonthermal radio-emitting bow shock and the thermal H II region. The spectral line images show that the radio recombination line comes from cold gas near the outer boundary of the bow shock and that the line intensity is enhanced by stimulated amplification of the nonthermal continuum emanating from the bow shock.

*Subject headings:* H II regions — radio lines: ISM

## 1. INTRODUCTION

G70.7+1.2 is a nonthermal radio-emitting bubble ~20″ in diameter inside a dense molecular globule. The origin of the nebula is controversial. Several astronomers over the years have speculated on its nature, and some suggestions include a young (~200 yr) supernova remnant (Reich et al. 1985), an ordinary H II region (Green 1986), a nebula created by Herbig-Haro outflow from a young stellar object (Becker & Fesen 1988), and a windblown bubble associated with a red giant at the end of the asymptotic giant branch (AGB) phase (de Muizon et al. 1988). None of these models can explain all the observed characteristics of G70.7+1.2.

Kulkarni et al. (1992) have proposed that G70.7+1.2 harbors a pulsar orbiting a B[e] star and that the bubble is supported primarily by the stellar wind of the B[e] star (see also Bally et al. 1989). In their model, the outflow of the B[e] star is mixed with the wind of energetic particles and magnetic fields from the neutron star. The combined pulsar-stellar wind creates a nonthermal, radio-emitting bow shock in the surrounding medium. Fabry-Perot observations of H$\alpha$ and [O I] emission lines provide strong evidence for a bow shock produced by supersonic motion of a mass-losing IR star through the molecular cloud (Kulkarni et al. 1992). Radio images of G70.7+1.2 at 8.4 GHz (see Fig. 2 of Kulkarni et al. 1992) also show the same parabolic bow shock morphology seen in the optical [O I] line emission. The Kulkarni et al. model provides a qualitative explanation for all the observed characteristics of the nebula. However, a pulsar has yet to be detected in the nebula.

In 1992 April we searched for evidence of an H II region in G70.7+1.2 by observing the nebula at the H168$\alpha$ recombination line transition frequency with a 3′.2 beam at the Arecibo radio telescope (Phillips, Onello, & Kulkarni 1993, hereafter Paper I). We successfully detected a line, but the spectral profile was very unusual. The line was dominated by a very narrow component ~3 km s$^{-1}$ wide, indicative of gas cooler than 185 K. G70.7+1.2 therefore contains the coolest known H II region. We followed up the Arecibo measurements with 99 GHz observations of G70.7+1.2 using the OVRO millimeter interferometer. We failed to detect a strong H40$\alpha$ line at 99 GHz and concluded that the centimeter-wavelength line was probably amplified by stimulated emission.

We also imaged the G70.7+1.2 nebula in the 99 GHz continuum (Paper I). The 99 GHz continuum emission arises primarily from two regions. The weaker of the two is centered on the bow shock and coincides roughly with a nonthermal source observed at lower frequencies (see, e.g., Kulkarni et al. 1992). The stronger region is about 5″ west of an IR star, has no obvious counterpart at centimeter wavelengths, and is probably a thermal H II region ionized by the IR star. In order to determine whether the narrow H168$\alpha$ line originates in the ambient gas ionized at the outer boundary of the bow shock or at the surface of the thermal H II region, we have made synthesis images of G70.7+1.2 at the H168$\alpha$ transition frequency using the C configuration of the VLA. In § 2 we describe our observations, and we discuss the results in § 3.

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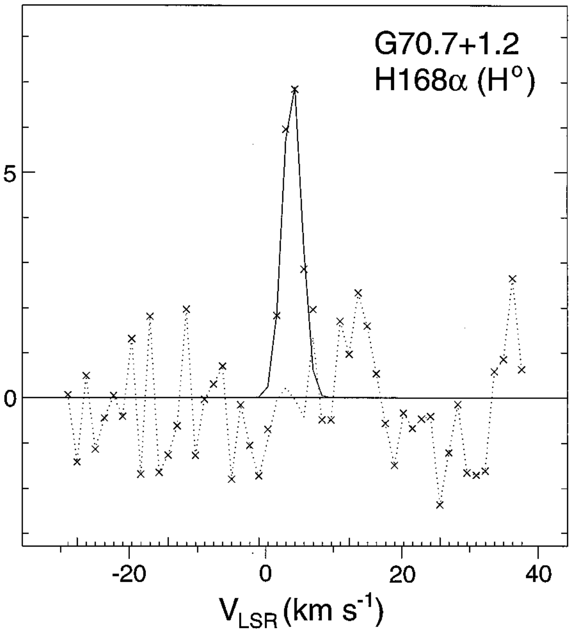

FIG. 1.—H168$\alpha$ ($H^0$) profile from G70.7+1.2. Data (*crosses*), residuals (*dotted line*), and model Gaussian fit (*solid line*) are plotted. Line parameters of the Gaussian fit are given in Table 1.

## 2. OBSERVATIONS

We observed G70.7+1.2 at the H168$\alpha$ (1374.6 MHz) transition in a single 10 hr run on 1994 October 13–14 using the C configuration of the VLA.[4] The H168$\alpha$ line was centered at a $V_{\rm LSR}$ of 3 km $s^{-1}$, and the total bandwidth for the observation was 0.78125 MHz. We set the phase center of the interferometer at the position of G70.7+1.2: $\alpha(1950) = 20^{\rm h}02^{\rm m}28^{\rm s}.0$, $\delta(1950) = 30°30'35''$ (Paper I). Two intermediate frequencies (IFs) with right- and left-circular polarizations (the 2AD correlator mode) were used, resulting in 256 spectral channels for each IF with a frequency separation of 3.052 kHz (with a resultant velocity resolution of 0.67 km $s^{-1}$). The flux density scale was set with the calibrator 3C 286 (1328+307), while the amplitude and phase were calibrated by interleaving observations of 1922+333 with observations of G70.7+1.2. We observed G70.7+1.2 for 400 minutes and the bandpass calibrator 1922+333 with a flux density of 3.7 Jy for 60 minutes.

The UV data were Fourier-transformed with natural weighting, and the resulting synthesized beam was $20'' \times 17''$ (P.A. 80°). The H168$\alpha$ line and radio continuum data were calibrated and processed using the standard data reduction procedures in the Astronomical Image Processing System (AIPS). Deconvolution of the dirty beams from images was achieved using the CLEAN algorithm. The AIPS task IMFIT was used to determine the deconvolved source size of the emitting region. The nominal fit to the peak channel of the emitting region is $21'' \times 12''$ (P.A. 90°). Additional data reduction for observed parameters, spatial distribution, and velocity structure of the narrow H168$\alpha$ line was performed using GIPSY (Groningen Image Processing System; van der Hulst et al. 1992). The rms noise level in the continuum image was 0.35 mJy $\rm beam^{-1}$. The H168$\alpha$ spectrum shown in Figure 1 was made by integrating over the region where the hydrogen line was observed. The rms noise level in the line cube is 1.05 mJy $\rm beam^{-1}$. The dotted line indicates the residuals after subtraction of a Gaussian profile. The VLA observed line parameters obtained from the Gaussian fit are listed in Table 1 and are in agreement with those reported (also listed in Table 1) in Paper I for Arecibo observations of G70.7+1.2.

TABLE 1

OBSERVED PARAMETERS FOR THE H168$\alpha$ ($H^0$) LINE OF G70.7+1.2[a, b]

| Parameters | VLA | Arecibo |
|---|---|---|
| $V_{\rm LSR}$ (km $s^{-1}$) | 3.9 ± 0.3 | 3.3 ± 0.1 |
| $\Delta V$ (km $s^{-1}$) | 3.3 ± 0.6 | 3.6 ± 0.1 |
| $S_L$ (mJy) | 7.2 ± 1.7 | 9.7 ± 0.3 |
| $\int_{\Omega_S} S_L(v)\,dv$ (mJy km $s^{-1}$) | 25 ± 7 | 37 ± 2 |

NOTE.—In this table $V_{\rm LSR}$ is the velocity of the line centroid with respect to the local standard of rest; $\Delta V$ is the full width at half-maximum of the line; $S_L$ is the flux of the line at maximum intensity; and $\int_{\Omega_S} S_L(v)\,dv$ is the line flux integrated over regions in the source with line flux greater than 3 $\sigma$.

[a] R.A.(1950) = $20^{\rm h}02^{\rm m}27^{\rm s}.5$, decl.(1950) = 33°30′35″.

[b] Source size = $21'' \times 12''$ (P.A. 90°).

## 3. DISCUSSION

Over the years since the first interferometric observations of radio recombination lines (RRLs) in H II regions were made (van Gorkom 1980), aperture synthesis imaging of the narrow hydrogen line ($H^0$) emission in H II regions has revealed that the line emanates from a partially ionized shell of cold hydrogen gas located between the H II region and an adjacent molecular cloud (Roelfsema 1990). Our observed narrow H168$\alpha$ ($H^0$) line velocity for G70.7+1.2 is very close to the $^{12}$CO velocity reported by Bally et al. (1989) and establishes the physical association of the thermal gas and the molecular cloud. The narrow width of the H168$\alpha$ line (FWHM = 3.3 km $s^{-1}$) shows that the gas must be cooler than 185 K and makes G70.7+1.2 the coldest known H II region. Normally the $H^0$ line discussed in the literature (Onello, Phillips, & Terzian 1991; Roelfsema & Goss 1992 and references therein) refers to the narrow hydrogen RRL, often observed with an associated carbon ($C^+$) line, emanating from partially ionized gas. No C168$\alpha$ emission line was observed at Arecibo for G70.7+1.2, and, based on the cosmic fractional abundance of [C/H], the absence of the carbon line argues that the gas may be fully ionized. In our paper $H^0$ means a narrow hydrogen RRL emitted from cold, fully ionized gas in G70.7+1.2. The nondetection of the $H^0$ line at 99 GHz reported in Paper I suggests that the 1.37 GHz RRL is stonger than LTE calculations would predict. In other H II regions with narrow $H^0$ lines at centimeter wavelengths, the lines are amplified by stimulated emission of an intense background source (Roelfsema & Goss 1992; Onello & Phillips 1993).

The 1.37 GHz continuum is a combination of nonthermal and thermal emission. We estimate the free-free contribution to the radio continuum by considering the observed integrated flux of 17 mJy for component A reported in Paper I. Component B in the OVRO map did not correspond to any well-defined feature in our 1.37 GHz image. Since the radio spectrum for G70.7+1.2 is very steep at high frequencies, we expect the nonthermal contribution to be weak and assume the 99 GHz emission to be thermal. Scaling the thermal flux at 99 GHz to that expected at 1.37 GHz through the $\nu^{-0.1}$ power law

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[4] The Very Large Array of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

and accounting for beam dilution of the source at the lower frequency, we estimate the thermal contribution to the total integrated flux to be 84 mJy. The observed integrated flux at 1.37 GHz was 1.0 Jy.

Using energy-balance arguments in Paper I, we suggested that the cold gas in G70.7+1.2 was ionized ≤100 yr ago and offered two possibilities for the origin of such young gas. In the "cloudlet" model, the narrow hydrogen profile arises at the surface of a cloudlet (H II region) that has been overtaken by the bow shock and is being ionized by Lyman continuum radiation from the IR star. For the "bow shock" model, the $H^0$ line emanates from new, ambient cold gas ionized at the outer boundary of a bow shock moving at ~100 km $s^{-1}$. Since the strong 8.4 GHz continuum emission reported by Kulkarni et al. (1992) was observed to overlie the region of the bow shock, we initially believed that the $H^0$ line most likely originated in cold gas in the foreground of the shock. However, the large 3.′2 Arecibo beam prevented us from determining which model was correct in explaining the ionization source responsible for the $H^0$ emission.

The primary goal of the investigation reported in this Letter was to image the continuum and line-emitting region of G70.7+1.2 to determine whether the narrow hydrogen RRL emanates from gas located in a cloudlet or near a bow shock. In Figure 2 (Plate L14) we present the 1.4 GHz continuum observations using the A configuration (gray scale; Wood 1995) overlaid with the contours of the peak channel of the H168$\alpha$ ($H^0$) line obtained at the VLA. As an aid to the discussion we have added a cross in Figure 2 to denote the position of the IR star and a component labeled "A" coinciding with the position of the nonthermal bow shock in the 8.4 GHz image of Kulkarni et al. (1992). The position of the bow shock region is clearly delineated (Fig. 2) in the high-resolution image of the G70.7+1.2 continuum at $\lambda = 20$ cm. Component B marks the position of the peak in the 99 GHz continuum image interpreted in Paper I as a thermal H II region ionized by the IR star. Observations of G70.7+1.2 using the B configuration (Goss & Benaglia 1995) with a resolution and sensitivity of 4″ and 1.7 mJy $\text{beam}^{-1}$, respectively, failed to detect any H168$\alpha$ line emission. The nondetection of the RRL is consistent with the deconvolved source size of 21″ × 12″ determined from the C configuration observations and indicates the lack of clumping for scale sizes less than 4″ in the emitting region.

If the bow shock model is correct, we would expect to observe the $H^0$ emission near the region labeled "A" and the peak of the $\lambda = 20$ cm emission in Figure 2. On the other hand, if the cloudlet model were correct, we would expect to see $H^0$ emission arising from the peak in the 99 GHz continuum, labeled "B" in the figure. As seen in Figure 2, the $H^0$ emission peaks closer to position A and the bow shock than to position B. Although the line-emitting region is only resolved for the long axis of the source using the C configuration, we are able to discern displacements smaller than the beam size because of the high signal-to-noise ratio of our data. Furthermore, the elongation of the emitting region (axial ratio ~2:1) is essentially parallel to the long axis of the shock front as observed in the high-resolution $\lambda = 20$ cm data. The observed spatial distribution of the H168$\alpha$ line in G70.7+1.2 indicates that the narrow $H^0$ emission feature arises primarily in new ambient gas recently ionized in the foreground of the bow shock produced by supersonic motion of a mass-losing IR star and not at the surface of a cloudlet ionized by the IR star.

J. S. O. wishes to thank the faculty and staff of the Department of Astronomy at Cornell University for their continuing support and warm hospitality. In particular, he wishes to thank Liese van Zee for illuminating discussions. He also gratefully acknowledges the joint New York State and United University Professions Committee for financial support in the form of a faculty development award.

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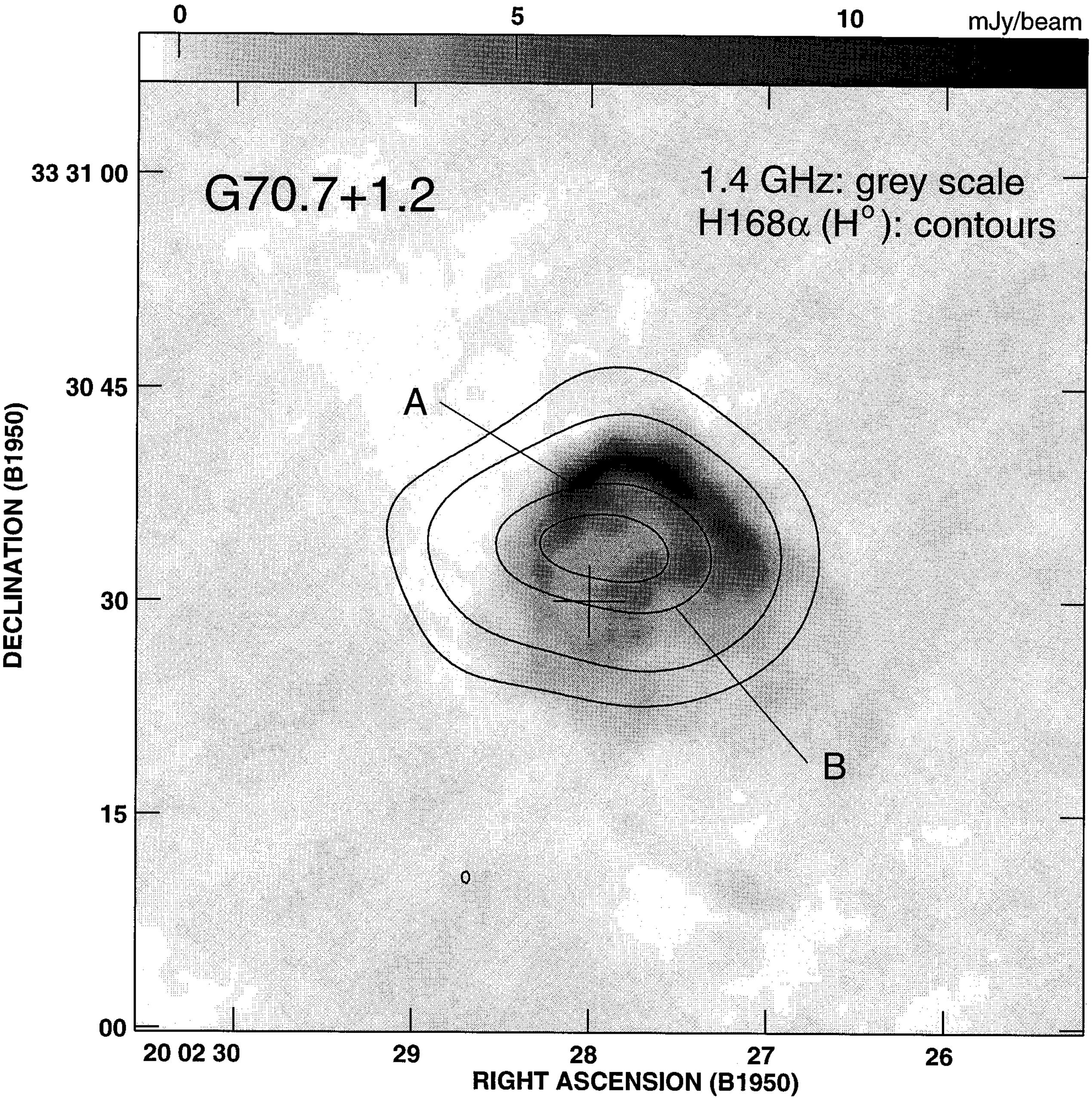

FIG. 2.—Overlay of the high-resolution 1.4 GHz continuum (Wood 1995) and the peak channel of the H168α ($H^0$) line emission. The peak 1.4 GHz continuum flux was 13.4 mJy $beam^{-1}$, and the continuum intensity gray scale is calibrated by the bar at the top of the figure. The cross denotes the position of the IR star discussed in Kulkarni et al. (1992), while "A" and "B" denote the positions of the nonthermal radio emission (bow shock) and the thermal 99 GHz peak, respectively. Contours of the H168α line emission are at −3, 3, 4.2, 6, and 6.6 mJy $beam^{-1}$.

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