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COMPACT RADIO SOURCES APPARENTLY ASSOCIATED WITH EXTENDED GALACTIC SOURCES

Alfonso Trejo and Luis F. Rodríguez

Centro de Radioastronomía y Astrofísica
Universidad Nacional Autónoma de México, Morelia, Michoacán, Mexico

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RESUMEN

Reportamos observaciones hechas con el VLA de la línea de 21 cm del HI hacia dos fuentes compactas que podrían estar asociadas con fuentes galácticas extendidas. En el caso de la nebulosa planetaria PHR 1735-333 observamos HI en absorción hacia una fuente de radio no térmica recientemente descubierta en la región, la cual se propuso estaba físicamente asociada con la nebulosa planetaria. Sin embargo, el análisis del espectro de HI en absorción sugiere una distancia mayor para esta fuente no térmica. En el caso del candidato a remanente de supernova SNR G3.8+0.3 obtuvimos espectros de HI en absorción hacia ella y hacia la fuente compacta de radio localizada en su centro. Concluimos que SNR G3.8+0.3 es más distante que la fuente compacta y que por lo tanto no están asociadas físicamente.

ABSTRACT

We report VLA radio observations of the 21 cm HI line toward two compact radio sources that could be associated with extended Galactic sources. In the case of the planetary nebula PHR 1735-333 we observed HI absorption against a non-thermal radio source recently discovered in the region, which was proposed to be physically associated with the planetary nebula. However, from the analysis of the HI absorption spectrum, we suggest a larger distance for this non-thermal source. In the case of the supernova remnant candidate SNR G3.8+0.3 we obtained HI absorption spectra towards it and towards a compact radio source located at its center. We conclude that SNR G3.8+0.3 is more distant than the compact radio source and that they are not physically associated.

Key Words: ISM: individual (SNR G3.8+0.3) — ISM: supernova remnants — planetary nebulae: individual (PHR 1735-333) — radio lines: ISM

1. INTRODUCTION

Compact radio sources sometimes appear associated in the plane of the sky with Galactic regions of extended emission. This association, if real, can be very important, since the compact source may be tracing the exciting source of the nebulosity or its interaction with other sources of energy such as the wind from a central star. On the other hand, we may just be dealing with a fortuitous line-of-sight alignment, with no real physical association. We have started a program of observations of such apparent associations using several techniques to determine the distance to the objects (Trejo & Rodríguez 2006, 2008, 2010), in an attempt to support or refute the association.

In this paper we present two cases of such an apparent association. One is the planetary nebula PHR 1735-333, and the other is the supernova remnant candidate SNR G3.8+0.3. In both cases we have been able to obtain HI absorption spectra that allow a determination of the distances to the sources and a better understanding of their nature. In both cases we favor a fortuitous line-of-sight alignment and propose that the compact source and the extended region of emission are not physically associated.

2. PHR 1735-333

The OH/IR star OH 354.88-0.54 (V1018 Sco) was detected as a mid-infrared point source in the Revised Air Force Geophysics Laboratory Rocket Sky

Survey of Price & Walker (1976) as source AFGL 5356. It was independently discovered as a strong 1612-MHz maser source during a survey of part of the Galactic plane (Caswell et al. 1981). Recently, Cohen, Parker, & Chapman (2005) discovered a planetary nebula around this star using data from the Anglo-Australian Observatory/United Kingdom Schmidt Telescope Hα Survey of the Southern Milky Way (Parker et al. 2005). This planetary nebula is named PHR 1735-333 in the MASH Planetary Nebula Catalog of Parker et al. (2006). There are several studies of this star involving different wavelengths. Green et al. (1999) found continuum emission associated with OH 354.88-0.54 in the first Molonglo Galactic Plane Survey at 843 MHz. The detected source was unresolved with a beam of approximately $1'$. Cohen et al. (2006) made a study of this source and its environment by means of 3, 6, 13 and 20 cm continuum and 1.3 cm line observations. These observations were taken with ATCA. Previously, only OH and SiO masers were reported in association with this source (e.g., Cohen et al. 2005; Nyman, Hall, & Bertre 1993), and Cohen et al. (2006) clearly detected water maser emission as well.

Cohen et al. (2006) found two non-thermal radio sources inside the planetary nebula (see Figure 1). Source A is relatively strong ($\sim$ 8 mJy at 20 cm) and partially resolved, while source B is weaker, unresolved and has no detection at 20 cm. The spectral indices of both sources are similar, -0.81 ± 0.01 and -0.95 ± 0.11, for A and B respectively. The sources lie at about the same projected angular distance from the central star. At 13 cm Cohen et al. found weak emission (2σ) apparently connecting both sources, but it is unclear if such extended emission is real. If confirmed, this connection would strengthen the possible association of sources A and B with the nebula.

It is well known that non-thermal emission can be found in massive stars (e.g., Abbott, Bieging, & Churchwell 1984; Persi et al. 1985). This non-thermal emission is believed to originate by embedded shocks in the stellar winds, as a faster component catches up with previous slower ejecta (White 1985). In a source such as PHR 1735-333, it can also be expected that the fast wind characteristic of the planetary nebula stage reaches and shocks the slow AGB wind, creating non-thermal emission.

In their study of PHR 1735-333, Cohen et al. (2006) proposed that the non-thermal radio sources were directly related to the nebula and not just line-of-sight alignments, since the probabilities of finding a single source at those positions are 1/500 and

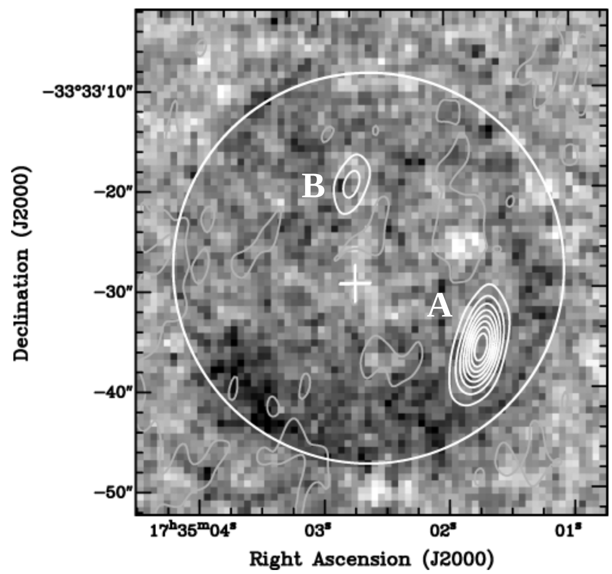

Fig. 1. Optical Hα image shown in grey, taken from the SuperCOSMOS database. The contours trace the 6 cm radio emission and show both non-thermal sources. The contours are 0.3, 0.5, 0.8, 1.1, 1.4, 1.6, 1.9, and 2.2 mJy beam^{-1}. The names of the sources (A & B) are as in Cohen et al. (2006). The cross marks the position of the star OH 354.88-0.54 and the white circle shows the approximate size of the PN candidate PHR 1735-333, which is visible in the optical image. This image is taken from Cohen et al. (2006).

1/200, for the observed 6 cm and 20 cm flux densities. The probability of finding two sources, if they are independent, will be much smaller ($\sim 10^{-5}$). The synchrotron emission would be generated, as they proposed, by the interaction between the slow AGB wind and the more recent fast wind from the nucleus of the PN. Since the presence of this type of interaction at relatively large distances from the star has not been reported in other sources and could be potentially very important, we tested the association of the non-thermal source A with the planetary nebula via HI absorption observations.

2.1. *Observations*

We made observations of the 21 cm HI line using the NRAO[1] Very Large Array in its B configuration. A total of 26 antennas were used at the L band. We observed on 2008 March 6 under project AR661 with a total on-source time of about 1.5 hours. We used a bandwidth of 3.125 MHz with the 2IF mode (both circular polarizations). A total of 64 channels, each

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

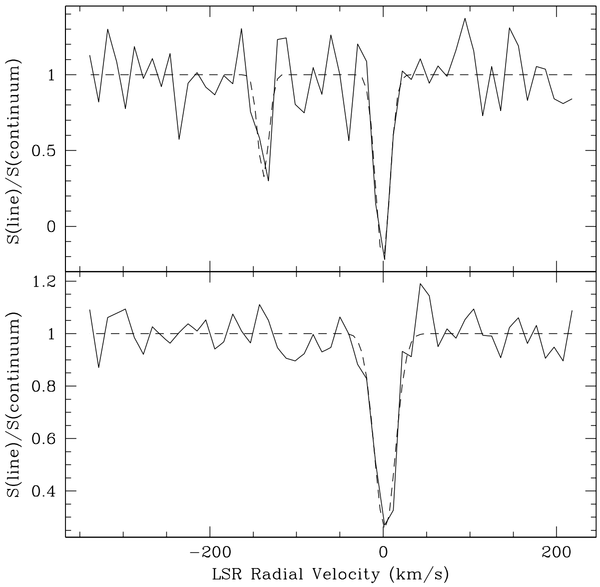

Fig. 2. Upper panel: Spectrum of the non-thermal source A seen in projection toward PHR 1735-333. The spectrum shows absorption at -140 km s^{-1}, which points to a farther location than that of the planetary nebula. Lower panel: Spectrum of a relatively strong Galactic source near the non-thermal source toward PHR 1735-333. It can be seen that the -140 km s^{-1} feature is not present in this last spectrum.

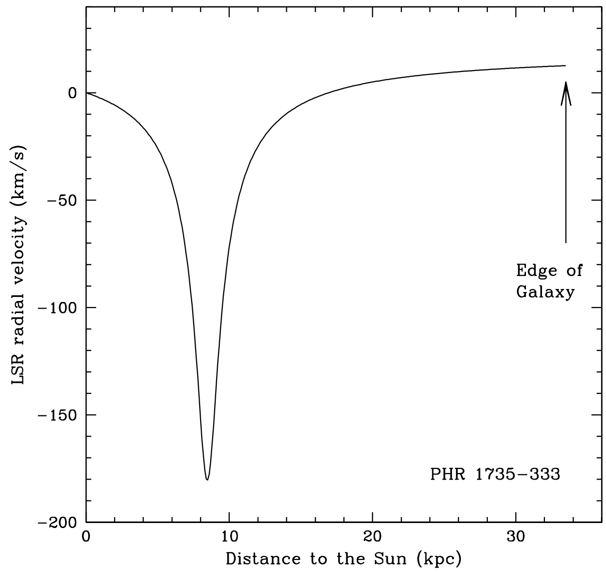

Fig. 3. LSR radial velocity as a function of distance to the Sun in the direction of PHR 1735-333. The positive values of the LSR radial velocity come from gas beyond the solar circle. The arrow marks the distance to the Sun where the edge of the Galaxy is located.

of 48.8 kHz wide, were used, which gave us a velocity resolution of 10.3 km s^{-1}.

We tried different weighting schemes in the task IMAGR, with ROBUST=0 (Briggs 1995) resulting as the best compromise between angular resolution and sensitivity. In order to avoid the emission of the Galactic plane we constructed images and spectra excluding baselines shorter that 0.7 Kλ (1 K$\lambda = 10^3$ wavelenghts), suppressing features more extended than $\sim 5'$. The data were processed in the standard manner, following the procedures of the AIPS Cookbook[2]. The beam had a half power full width of $34\rlap{.}''3 \times 12\rlap{.}''8$, PA= $3\rlap{.}^\circ5$, with a positional accuracy of $\sim 3''$.

2.2. *Results and discussion*

The main goal of these observations was to obtain an HI absorption spectrum of the brighter non-thermal source (source A) seen toward the planetary nebula PHR 1735-333, with the purpose of constraining its distance and testing its association with the PN. As the target source turned out to be weak at the epoch of observation, we got a spectrum with modest signal to noise ratio (see top panel of Figure 2), with two absorption features. Since the continuum and the line are observed simultaneously and are perfectly aligned, we only need to determine the peak of the continuum emission and there take the spectra. The values for the HI absorption features are $S_{\rm L}/S_{\rm C} = -1.22 \pm 0.15$ (7.9σ), $V_{\rm LSR} = -0.6 \pm 1.4$ km s^{-1} and $\Delta V = 19.5 \pm 2.8$ km s^{-1} for one, and $S_{\rm L}/S_{\rm C} = -0.68 \pm 0.15$ (4.5σ), $V_{\rm LSR} = -138.3 \pm 2.7$ km s^{-1} and $\Delta V = 15.0 \pm 4.6$ km s^{-1} for the other, where S_L/S_C is the normalized ratio between line and continuum flux densities, $V_{\rm LSR}$ is the radial velocity of the component referred to the local standard of rest, and ΔV stands for the full width at half minimum of the fitting. In the case of the Galactic source near PHR 1735-333 (see lower panel of Figure 2), the HI absorption feature has $S_{\rm L}/S_{\rm C} = -0.75 \pm 0.04$ (18.8σ), $V_{\rm LSR} = +1.9 \pm 0.8$ km s^{-1} and $\Delta V = 28.7 \pm 1.9$ km s^{-1}. We considered as real only features above 4σ. Figure 2 shows the spectra and the fit superposed on it. The derived line widths are broadened by the instrumental resolution (10.3 km s^{-1}) and the deconvolved values are ~ 17 and ~ 11 km s^{-1} for the two absorption components shown in the upper panel of Figure 2, and ~ 27 km s^{-1} for the absorption shown in the lower panel of Figure 2. The HI absorption at a $V_{\rm LSR}$ near 0 km s^{-1} is attributed to nearby gas.

[2]http://www.aips.nrao.edu/cook.html.

TABLE 1

SOURCES IN THE FIELD OF PHR 1735-333 FOR WHICH HI SPECTRA WERE EXTRACTED

	Position		20 cm Flux
Source	α(J2000)	δ(J2000)	Density (mJy)
OH 354.88-0.54 A	17 35 01.734	−33 33 36.36	2.7 ± 0.5
Galactic source	17 35 00.070	−33 24 17.10	20.5 ± 0.5

On the other hand, considering the rotation curve of the Galaxy (Brand & Blitz 1993) and assuming that the HI disk of the Galaxy has an outer radius of 25 kpc (Dickey et al. 2009), we show in Figure 3 the LSR velocity versus distance to the Sun for a source at the Galactic latitude and longitude of PHR 1735-333. From this figure we can see that if the non-thermal source A is associated with the PN, we expect HI absorption components with LSR radial velocities only in the 0 to -11 km s^{-1} range. In contrast, if the radio source is extragalactic we expect possible HI absorption components from 0 to -180 km s^{-1}. In addition, HI absorption at positive velocities (0 to +13 km s^{-1}) may be detected from gas outside the solar circle and located on the other side of the Galaxy.

Then, the absorption feature at approximately -140 km s^{-1} suggests that the gas responsible for that absorption is located at more than 8 kpc, according to Figure 3. We then propose that this non-thermal source is not related to the planetary nebula, which is located at a smaller distance of 3.2 kpc (Cohen et al. 2005). It should be noted, however, that the detection of the -140 km s^{-1} absorption feature is at the level of only 4.5σ level and that additional studies are required to be fully confident that the source A is more distant than the planetary nebula.

The position and flux density of this non thermal source is given in Table 1. For comparison, we plot in the lower panel of Figure 2 an example of a spectrum of another source present in the field observed. There is very little information on this source. It is detected in the NRAO VLA Sky Survey (Condon et al. 1998) with a 1.4 GHz flux density of 21.6 ± 0.6 mJy, in good agreement with the value found by us (see Table 1). Since it shows HI absorption only near 0 km s^{-1}, we will assume it is a nearby Galactic source. We can see that the spectrum towards this source does not present the absorption feature at ~ -140 km s^{-1}.

Finally, Cohen et al. (2006) reported a 20 cm flux density of 7.68 ± 0.18 mJy for the non-thermal source A, from their 2005 March 24 observations. We found this flux to be of only 2.7 mJy (see Table 1) in our 2008 March 6 observations. As we noted before, source A could be an extragalactic object, such as a quasar. Then, a change in the flux density by a factor of ~ 3 is not unexpected for this type of sources. However, it should be noted that changes have also been observed in some planetary nebulae (Gómez et al. 2005; Zijlstra, van Hoof, & Perley 2008). This decrease in flux density was unfortunate, since it reduced the signal-to-noise ratio of the HI absorption spectrum toward source A. It will be interesting to study from the theoretical point of view if flux density changes of this order and timescale can be produced by the interaction of two winds.

3. SNR CANDIDATE G3.8+0.3

The radio continuum source SNR G3.8+0.3 is a supernova remnant candidate that was detected by Gray (1994) in the Molonglo Observatory Synthesis Telescope (MOST) Galactic center survey made at 843 MHz. As noted by Gray, this source shows an incomplete ring almost perfectly centered on a compact source (see Figure 4). The supernova remnant candidate has been studied by Bhatnagar (2002) at 327 MHz, who determined a spectral index of $\alpha = -0.6 \pm 0.1$ ($S_\nu \propto \nu^\alpha$) between 327 and 843 MHz. This result implies a synchrotron origin for the emission and strongly supports a supernova remnant nature for the extended radio source. Case & Bhattacharya (1998) used a radio surface brightness-to-diameter (Σ-D) relation to estimate a distance of 9.6 kpc to SNR G3.8+0.3, while Stupar et al. (2007) obtain a distance of 7.7 kpc from a different relation. We adopt an estimate of 8.7 ± 1.0 kpc for the distance to the SNR. Examination of available Hα survey imaging data such as for the AAO/UKST H-alpha survey (Parker et al. 2005) reveals no evidence of optical emission from the SNR candidate. There are no known X-ray sources or pulsars associated with this SNR candidate.

The compact radio source at the center of SNR candidate G3.8+0.3 is associated with the source

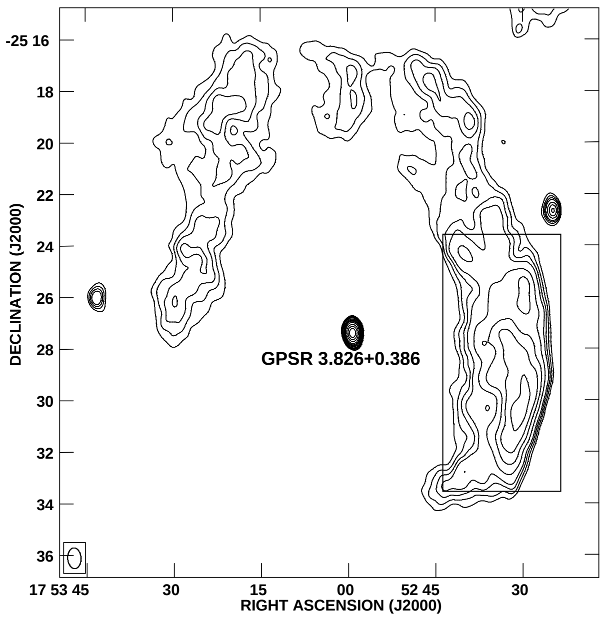

Fig. 4. VLA contour image of the continuum emission at 1.5 GHz of the supernova remnant candidate SNR G3.8+0.3. Contours are 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, and 30 times 0.5 mJy beam^{-1}. The image is not corrected for the primary beam response (the observations were made centered at the position of the phase calibrator 1751–253 at $\alpha(2000) = 17^h\ 51^m\ 51\overset{s}{.}265; \delta(2000) = -25^\circ\ 23'\ 59\overset{''}{.}80$) and the eastern edge of the shell appears weaker in comparison to the western edge than it really is. The compact source GPSR 3.826+0.386 is labeled in the figure. The rectangle indicates the region over which the HI absorption spectrum of the SNR candidate was obtained. The half-power contour of the synthesized beam ($48\overset{''}{.}4 \times 30\overset{''}{.}8$; PA=3°) is shown in the bottom left corner of the image.

IRAS 17498–2526. This far-infrared source was proposed to be a possible planetary nebula by Preite-Martínez (1988) and Pottasch et al. (1988) on the basis of its IRAS colors. However, it should be noted that this association is uncertain. The radio source is listed in the catalog of small-diameter radio sources in the Galactic plane of Zoonematkermani et al. (1990) as GPSR 3.826+0.386 and we use this nomenclature to refer to it. These authors determine at 1.4 GHz a flux density of 45 mJy and an angular size of $2\overset{''}{.}3$ for the source. In their 5 GHz VLA survey of the Galactic plane, Becker et al. (1994) report the source with a flux density of 50.7 mJy and an angular size of $3\overset{''}{.}1$. The flat spectrum observed between 1.4 and 5.0 GHz is consistent with an optically-thin free-free source such as a planetary nebula or an HII region. The *a priori* probability of finding a ~ 50 mJy source at 5 GHz in a region with angular dimensions of $2' \times 2'$ (that approximately define the center of the SNR remnant candidate) is only ~ 0.0003 (Fomalont et al. 1991). The position of GPSR 3.826+0.386 is $\alpha(2000) = 17^h\ 52^m\ 59\overset{s}{.}28; \delta(2000) = -25^\circ\ 27'\ 24\overset{''}{.}7$. The images of the AAO/UKST Hα survey (Parker et al. 2005) show that this source is a strong and compact Hα emitter (see Figure 5) and that optical spectroscopy should be pursued.

3.1. *Observations*

SNR G3.8+0.3 has practically not been observed with the VLA. Fortunately, it is located at $\sim 15'$ from the well known VLA phase calibrator 1751–253 that has been extensively observed. We have then used data centered on 1751–253 to study SNR G3.8+0.3. Although the latter source is located at a position where the primary beam response at 20 cm of the 1751–253 observations is ~ 0.5 of that at the center, the observations can be used taking this factor into account.

In Figure 4 we show a 1.5 GHz image made with archive VLA data taken on 1984 May 31 as part of project AE32. The VLA was then in the C configuration and the absolute amplitude calibrator was 1331+305. The bootstrapped flux density of 1751–253 was 1.24 ± 0.01 Jy. The image shows the incomplete shell morphology of SNR G3.8+0.3 and the central location of GPSR 3.826+0.386.

The HI observations, made in 1989 October 21 as part of project AL201, were taken from the archive of the Very Large Array. The VLA was then in the C configuration, providing an angular resolution of about $40''$ for images made with natural weighting. The absolute amplitude calibrator was 1331+305 (with an adopted flux density of 14.73 Jy at 1.4 GHz). The bootstrapped flux density of 1751–253 was 1.02 ± 0.01 Jy. The data were edited and calibrated using the software package Astronomical Image Processing System (AIPS) of NRAO. The spectra consisted of two windows, one centered below in frequency (1419.406 MHz) and the other above in frequency (1421.406 MHz) of the HI rest frequency (1420.406 MHz). Each window had 127 channels of 24.4 kHz (5.2 km s^{-1}) each. In order to avoid the emission of the Galactic plane we made images and spectra excluding baselines shorter that 0.5 Kλ, supressing features more extended than $\sim 7'$. We analyzed separately each window and overlapped them to produce a single spectrum for the sources studied.

3.2. *Results and discussion*

In Figure 6 we show the HI absorption spectra toward three sources in the field: the phase calibrator 1751–253, the brightest part of the western shell

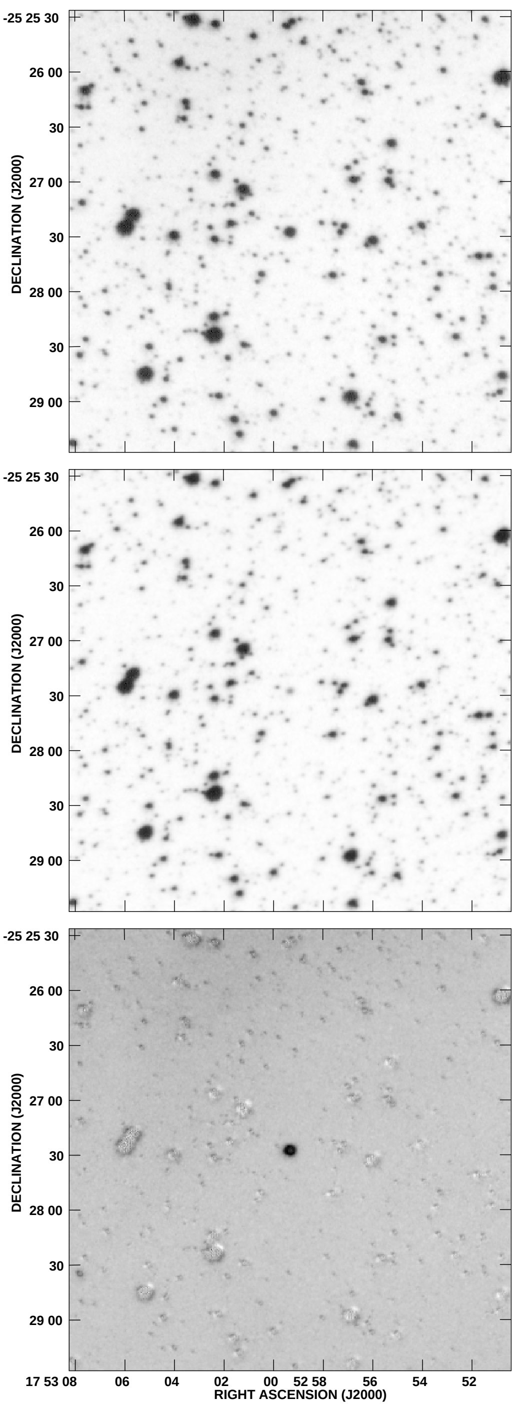

Fig. 5. 4 × 4 arcmin extracts of the AAO/UKST Hα SuperCOSMOS survey (Parker et al. 2005) around the compact source GPSR 3.826+0.386. Top: Hα emission; center: short red emission; bottom: Hα minus short red emission. Only GPSR 3.826+0.386 remains detectable in the bottom image, indicating it is a strong Hα emitter. The weaker features in this last image are the result of an imperfect subtraction.

of SNR G3.8+0.3, and the compact source GPSR 3.826+0.386.

To help in the discussion, we show in Figure 7 the LSR velocity versus distance to the Sun for a source at the Galactic latitude and longitude of GPSR 3.826+0.386, obtained as for the case of PHR 1735-333. The phase calibrator $1751-253$ is an extragalactic source and, as expected, its HI absorption spectrum confirms this. The spectrum shows strong absorption near 0 km s^{-1}, as expected since most of the gas in the direction of this region appears near the LSR radial velocity. In addition, the absorption spectrum shows a clear feature at +160 km s^{-1} that is coming from gas close to the subcentral point. Finally, this spectrum also shows absorption at -41 km s^{-1}, that is coming from beyond the solar circle. Our HI spectrum is in good agreement with that presented by Dickey et al. (1983), although these authors do not cover a sufficiently large velocity interval to include the +160 km s^{-1} feature.

The HI spectra of SNR G3.8+0.3 and GPSR 3.826+0.386 both show absorption around 0 km s^{-1}. However, the spectrum of SNR G3.8+0.3 clearly shows an absorption at +170 km s^{-1} which places this supernova remnant candidate beyond the subcentral point, at 8.5 kpc. This lower limit for the distance is consistent with the value estimated from the results of Case & Bhattacharya (1998) and Stupar et al. (2007), 8.7 ± 1.0 kpc. In contrast, GPSR 3.826+0.386 does not show this absorption, suggesting it is closer to us than the subcentral point. This upper limit for the distance is consistent with the value of 1.7 kpc estimated by Preite-Martínez (1988), from a modified Shklovski (statistical) method applied to all the planetary nebulae in his sample. We then conclude that the supernova remnant candidate and the compact source are most likely not associated.

4. CONCLUSIONS

We made HI line radio observations toward the planetary nebula PHR 1735-333 and analyzed archive data of the supernova remnant candidate SNR G3.8+0.3. Both sources are associated in the plane of the sky with compact radio sources that could be physically related to them. Our study shows that the distance to the non-thermal radio source recently found in apparent association with the planetary nebula PHR 1735-333 is at least two times larger than that of the nebula. We conclude that the radio source is most probably unrelated to the Galactic planetary nebula and we suggest an extragalactic nature for it. However, there are several arguments that favor the association as real: (i) the

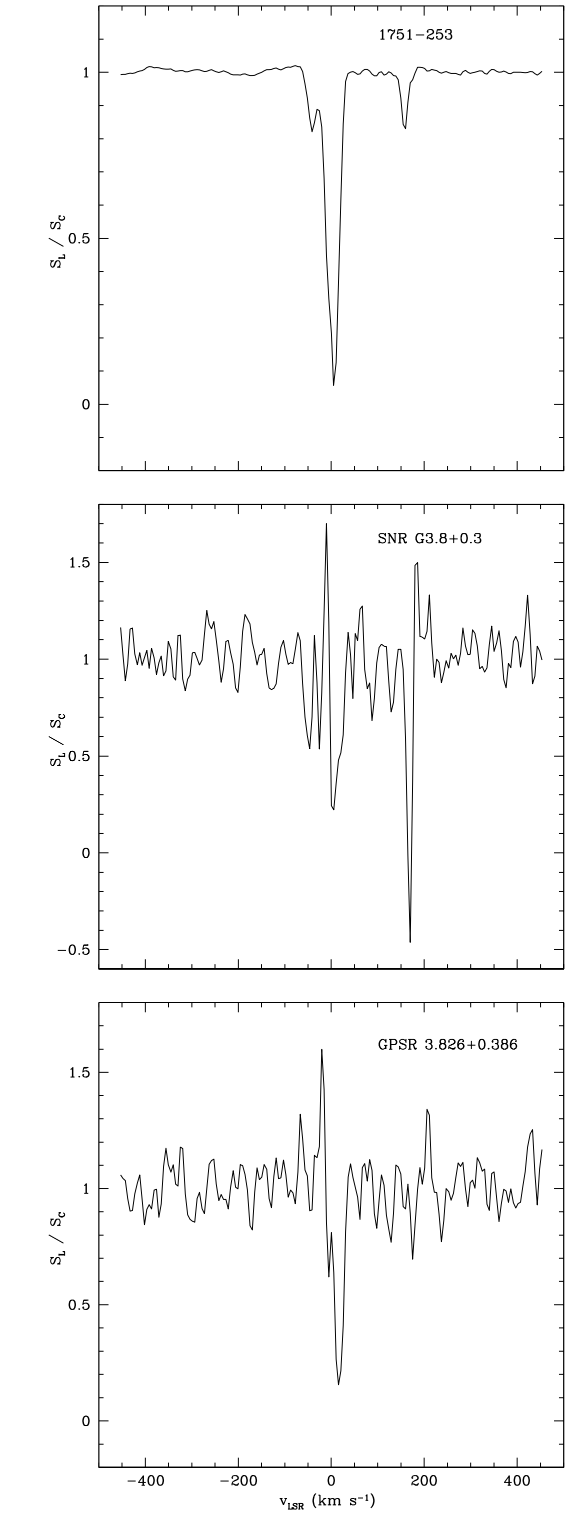

Fig. 6. 21 cm H I absorption spectra for the three sources discussed in the text, plotted as a function of LSR radial velocity. The measured spectra were divided by the continuum level ($-\tau_v$), where τ_v is the opacity as a function of velocity.

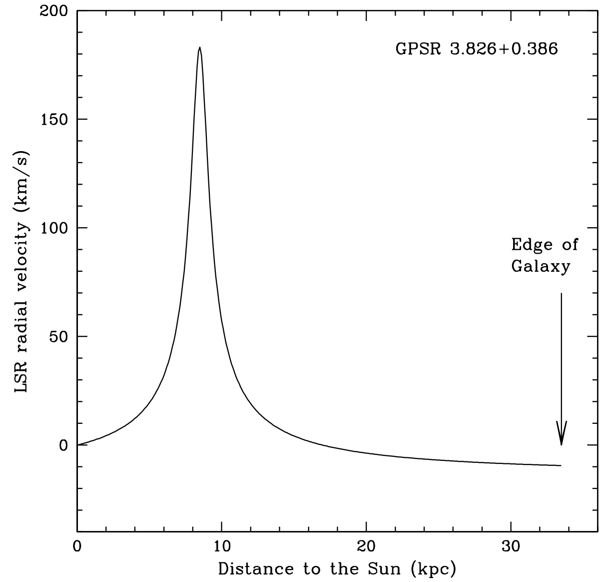

Fig. 7. LSR radial velocity as a function of distance to the Sun in the direction of GPSR 3.826+0.386. The negative values of the LSR radial velocity come from gas beyond the solar circle. The arrow marks the distance to the Sun where the edge of the Galaxy is located.

low probability of detection of two sources within the PN shell (see above), (ii) the possible link between them at 13 cm, (iii) the fact that the radio sources are equidistant from the compact central source, and (iv) the low signal-to-noise ratio of the HI detection at source A. Additional observations are clearly required.

In the case of the supernova remnant candidate SNR G3.8+0.3, we conclude that it is located beyond the subcentral point, at more than 8.5 kpc from the Sun, while the compact source GPSR 3.826+0.386 is located closer than the subcentral point and thus the two sources are not physically associated.

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Alfonso Trejo and Luis F. Rodríguez: Centro de Radiostronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72, (Xangari), 58089 Morelia, Michoacán, Mexico (a.trejo, l.rodriguez@crya.unam.mx).