A&A 562, A108 (2014)
DOI: 10.1051/0004-6361/201321571

Astronomy & Astrophysics

Search for 150 MHz radio emission from extrasolar planets in the TIFR GMRT Sky Survey★

S. K. Sirothia[1], A. Lecavelier des Etangs[2,3], Gopal-Krishna[1], N. G. Kantharia[1], and C. H. Ishwar-Chandra[1]

[1] National Centre for Radio Astrophysics, TIFR, Post Bag 3, Pune University Campus, 411007 Pune, India
[2] CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98[bis] boulevard Arago, 75014 Paris, France
e-mail: lecaveli@iap.fr
[3] UPMC Univ. Paris 6, UMR 7095, Institut d'Astrophysique de Paris, 98[bis] boulevard Arago, 75014 Paris, France

Received 26 March 2013 / Accepted 7 January 2014

ABSTRACT

The ongoing radio continuum TIFR GMRT Sky Survey (TGSS) using the Giant Metrewave Radio Telescope (GMRT) at 150 MHz offers an unprecedented opportunity to undertake a fairly deep search for low-frequency radio emission from nearby extrasolar planets. Currently TGSS images are available for a little over a steradian, encompassing 175 confirmed exoplanetary systems. We have searched for their radio counterparts in the TGSS (150 MHz), supplemented with a search in the NRAO VLA Sky Survey (NVSS) and the VLA FIRST survey at 1.4 GHz. For 171 planetary systems, we find no evidence of radio emission in the TGSS maps, placing a 3σ upper limit between 8.7 mJy and 136 mJy (median ~24.8 mJy) at 150 MHz. These non-detections include the 55 Cnc system for which we place a 3σ upper limit of 28 mJy at 150 MHz. Nonetheless, for four of the extrasolar planetary systems, we find TGSS radio sources coinciding with or located very close to their coordinates. One of these is 61 Vir: for this system a large radio flux density was predicted in the scenario involving magnetosphere-ionosphere coupling and rotation-induced radio emission. We also found 150 MHz emissions toward HD 86226 and HD 164509, where strong radio emission can be produced by the presence of a massive satellite orbiting a rapidly rotating planet. We also detected 150 MHz emission within a synthesized beam from 1RXS1609 b, a pre-main-sequence star harboring a ~14 Jupiter mass planet (or a brown dwarf). With a bright X-ray-UV star and a high mass, the planet 1RXS1609 b presents the best characteristics for rotation-induced emissions with high radio power. Deeper high-resolution observations toward these planetary systems are needed to discriminate between the possibilities of background radio-source and radio-loud planets. At 1.4 GHz, radio emission toward the planet-harboring pulsar PSR B1620-26 is detected in the NVSS. Emissions at 1.4 GHz are also detected toward the very-hot-Jupiter WASP-77A b (in the FIRST survey) and the giant planet HD 43197 b in a highly eccentric orbit (in NVSS). We briefly discuss these detections, as well as the non-detection of the vast majority of exoplanets.

Key words. radio continuum: general – planetary systems – planets and satellites: detection

1. Introduction

The detection of radio emission from extrasolar planets would be a major advance in exoplanetology. Since the radio-frequency emission from planets is expected to be strongly influenced by its interaction with the magnetic field and corona of the host star, the physics of such an interaction can be effectively probed by measurement of the planetary radio emission. Theoretical estimates for radio emission from extrasolar planets have shown that their radio detection is within present capabilities, in particular with the GMRT observing down to 150 MHz with milli-Jansky sensitivity. For instance, Grießmeier et al. (2007) and Zarka et al. (2007) considered star-planet interaction, and Nichols (2011, 2012) considered fast rotating planets with magnetosphere-ionosphere coupling with internal plasma sources (like moons) as possible sources of auroral radio emission even for planets with large orbital distances. In any event, it should be emphasized that all the theoretical estimates of cyclotron maser decametric emission are based on a host of unknowns, e.g., stellar winds, coronal density, and stellar and planetary magnetic fields.

With this possibility in mind, pointed searches for radio continuum emission from a few planetary systems have been undertaken at decameter and meter wavelengths (see reviews in Lazio et al. 2009; and Zarka 2011). More recently, similar attempts include the search toward HD 80606 (Lazio et al. 2010), HD 189733 b and HD 209458 b (Lecavelier des Etangs et al. 2009, 2011), and τ Boo (Hallinan et al. 2013). To date, the results of all searches for radio emission from exoplanets have been negative. At these low frequencies, the principal contributors to the noise level are the sky background, radio frequency interference and the ionospheric scintillations which distort the incoming signal and increase the noise. Hence, high-resolution interferometric observations at high level of sensitivity hold considerable promise. In particular, the Giant Metrewave Radio Telescope (GMRT), a 25 km baseline array consisting of 30 dishes, each with a diameter of 45 m (Swarup 1990), is very appealing for this purpose.

Based on a GMRT deep search targeted at the planets HD 189733 b and HD 209458 b, the two best candidates among the known hot-Jupiter class of extrasolar planets, we reported 3σ upper limits for the stellar+planetary emission, of 2 mJy at 244 MHz and 160 μJy at 614 MHz (Lecavelier des Etangs et al. 2009). Because one of the viable explanations for the non-detection is the emission frequency being still lower owing

★ Full Table 1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/562/A108 to a weak planetary magnetic field, radio searches have been performed at 150 MHz which is the lowest frequency accessible using the GMRT. At this frequency, a careful data analysis allowed the derivation of 3σ upper limits of 2 and 4 mJy for HD 189733 b and HD 209458 b, respectively (Lecavelier des Etangs et al. 2011), and 1.2 mJy for τ Boo (Hallinan et al. 2013). Nonetheless, observation of secondary eclipses of the hot-Neptune class exoplanet HAT-P-11b gave a hint of detection of radio emission from the planet with a flux density of 3.9 ± 1.3 mJy at 150 MHz (Lecavelier des Etangs et al. 2013). However, further observations are required to reach a definitive conclusion.

Up to now all searches for radio emission from exoplanets have been targeted searches. An alternative approach would be to make moderately deep but wide-area searches now afforded by a sensitive low-frequency radio survey like the ongoing TIFR GMRT Sky Survey (TGSS), an imaging survey designed to cover 37 000 square degrees (~91%) of the sky at 150 MHz, a frequency at which emissions from exoplanets can be expected, for planetary magnetic fields above ~50 G.

Here we present an attempt to search for radio continuum emissions from exoplanets in the TGSS (at 150 MHz). We also complemented the search using the NRAO VLA Sky Survey (NVSS) and the VLA FIRST survey (both at 1.4 GHz). The FIRST survey produced Faint Images of the Radio Sky at Twenty centimeters using the VLA (Becker et al. 1995). This survey is the radio equivalent of the Palomar Sky Survey, mapping 9900 square degrees of the sky to a flux density limit of 1 mJy at 20 cm wavelength with 5″ resolution. The NVSS covers the sky north of declination –40° (82% of the sky) at 1.4 GHz (Condon et al. 1998). The associated catalog contains almost 2×10^6 discrete sources stronger than $S \sim 2.5$ mJy. In comparison, TGSS offers a better prospect for exoplanet search because its lower frequency requires weaker planetary magnetic field for cyclotron emission. However because the exoplanets' magnetic fields are unknown, a significantly larger target list provided by NVSS and FIRST can be considered. We first briefly discuss possible implications of the non-detected majority (Sect. 2). Thereafter, we present the cases of seven exoplanetatary systems for which we find possible radio counterparts (Sect. 3). The results will be briefly discussed in Sect. 4.

2. The TGSS and the known exoplanets

2.1. The TGSS

The TIFR GMRT Sky Survey (TGSS) is a radio continuum survey at 150 MHz made with the GMRT. This survey typically reaches an rms noise of 7 mJy per beam with an angular resolution of about 20″.There is no polarization information. The complete survey will cover about 37 000 square degree of the sky north of –55°declination.

To identify possible emissions from exoplanets, we compared the TGSS source list with the coordinates of exoplanets appearing in the Extrasolar Planets Encyclopaedia maintained by Dr. Jean Schneider from the Paris Observatory[1]. We used the 25 January 2013 version, which includes a total of 859 planets belonging to 677 planetary systems.

In the 5th release of the TGSS, corresponding to a fraction of about 10% of the full TGSS, 150 MHz images are available for the fields of 175 exoplanetary systems. Out of these, 111 systems have only one known planet. Out of the remaining 64 (multi-planetary) systems, 46 systems are known to host at least 2 planets, 11 systems host 3 planets, 4 systems host 4 planets, and 3 systems host 5 planets, including the very nearby system 55 Cnc located 12.3 pc from the Sun. The 55 Cnc system includes the transiting planet 55 Cnc e with a very short orbital period of less than 18 h.

Table 1. The rms flux density at 150 MHz toward the exoplanets' host stars as measured in the TGSS maps.

Planetary system	Right asc. (J2000)	Declination (J2000)	Dist. (pc)	rms (mJy)
14 And	23:31:17.000	+039.14.10.000	76.4	5.2
16 Cyg B	19:41:51.000	+050.31.03.000	21.4	11.2
55 Cnc	08:52:37.000	+028.20.02.000	12.3	9.3
BD-10 3166	10:58:28.000	–010.46.13.000	66.0	6.2
CoRoT-10	19:24:15.000	+000.44.46.000	345.0	29.1
CoRoT-3	19:28:13.000	+000.07.19.000	680.0	9.1
GJ 317	08:40:59.000	–023.27.23.000	15.1	3.9
GJ 3634	10:58:35.000	–031.08.39.000	19.8	4.5
GJ 433	11:35:27.000	–032.32.24.000	9.0	11.4
GQ Lup	15:49:12.000	–035.39.03.000	140.0	20.9

Notes. Here is an extract of the complete table (171 lines), which is available in CDS.

We checked the TGSS maps in the directions of the 175 known extrasolar planetary systems. Cases when a source with a ≥3σ peak appears within a distance from the host star position, that is less than or equal to the half power beam-width are treated as interesting radio detections. We do not claim that this implies that the detected emission comes from the planet, but only that if a source is detected within a beamsize from a planet hosting star, it merits further analysis and observations. We found 4 such cases which will be presented in Sect. 3. For the remaining 171 planetary systems, we are left with non-detections with a 3σ upper limit on the flux density, where σ is the root mean squared (rms) of residuals in the map at the system coordinates. These non-detections are listed in Table 1. The corresponding values of σ range from 2.9 to 45 mJy, with a median of 8.3 mJy.

Because the distances (d) of each planetary system is known (see Table 1), the 3σ upper limit on its flux density can be converted into an upper limit on the intrinsic 150 MHz radio-luminosity of the system ($L_{\rm upper} = 3 \times {\rm rms} \times 4\pi d^2$). Thus, for the non-detections, we have plotted these 3σ upper limits on the radio-luminosity against the planets' orbital semi-major axes and mass (Figs. 1 and 2). From this the typical radio-luminosity of these planetary systems can be inferred to be below $\sim 10^5$–10^6 mJy pc^2 at 150 MHz (or $\sim 10^9$–10^{10} W Hz^{-1}; a value even an order of magnitude lower value may be possible if the emissions are strongly beamed). The points below this limiting luminosity are seen to populate a wide range of orbital distances (from ~0.03 au to ~5 au) and planetary masses (from ~3 Earth mass to ~10 Jupiter mass). Hence, they are likely to represent a wide diversity of the planetary types. The non-detections plotted at larger radio luminosities then probably represent such high upper limits mainly because their distances from us are relatively large.

2.2. The 55 Cnc planetary system

Among the 171 systems undetected at 150 MHz, 55 Cnc deserves special attention. This system is known to have a large number of planets (at least five), one of which, the giant planet 55 Cnc b, is thought to have an extended upper atmosphere of

[1] www.exoplanet.eu

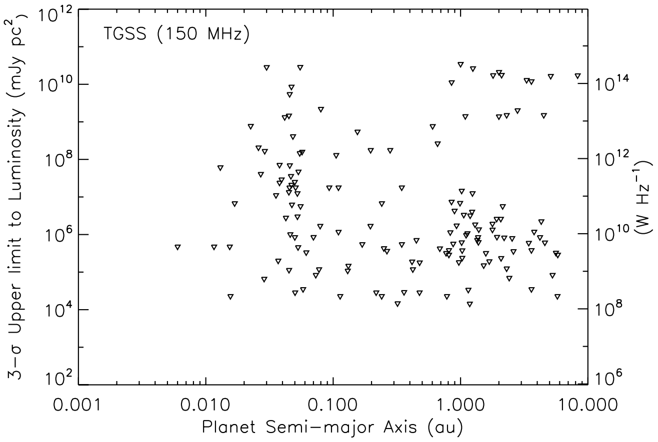

Fig. 1. For the 171 planetary systems undetected in TGSS, upper limits on the intrinsic 150 MHz radio-luminosity are plotted against the planets' orbital semi-major axis.

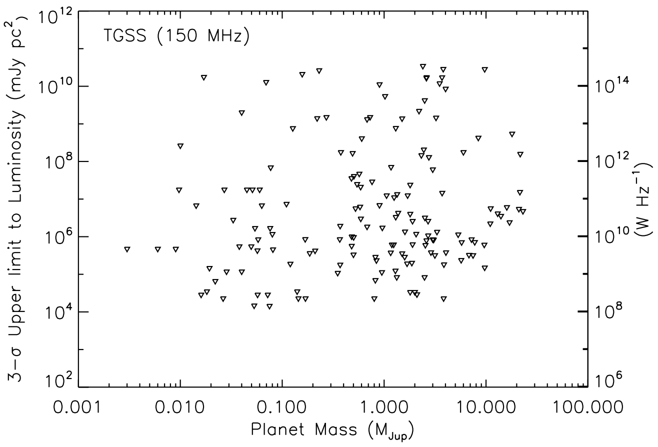

Fig. 2. For the 171 planetary systems undetected in TGSS, upper limits on the intrinsic 150 MHz radio-luminosity are plotted against the planetary mass.

escaping hydrogen (Ehrenreich et al. 2012). More importantly, 55 Cnc e is close to the Earth and orbits in less than 18 h (Dawson & Fabrycky 2010) with an orbital distance of 0.0156 AU, that is only 3.3 $R_{\odot}$. With such a small star-planet distance, the planet is embedded well within the stellar corona of the host K0V star. In addition, with a distance of just 12.3 parsec from the Earth, this planetary system is among the best targets to search for radio emission.

We carried out analysis of the available GMRT observations at 150 MHz obtained within the TGSS. This allowed placing a 3σ upper limit of about 28 mJy for the radio-emission toward 55 Cnc.

The planet 55 Cnc e is the archetype for the scenario developed by Jardine & Cameron (2008) in which the stellar magnetosphere extends beyond the orbit of its planet(s), and radio emission is produced as the result of the interaction between the planetary magnetosphere and the engulfing stellar corona. They applied this model to the case of the planet HD 189733 b located 19.3 pc away. Taking a stellar magnetic field strength of 40 G (Moutou et al. 2007), an orbital distance of 0.03 au, an orbital period of 2.218 days, a stellar rotation period of 11.73 days, a 10% efficiency of conversion of the power of accelerated electrons into radio emission, and a solid angle of the emission beam of 1.6 sr, they derived a theoretical estimate of 15 mJy for this

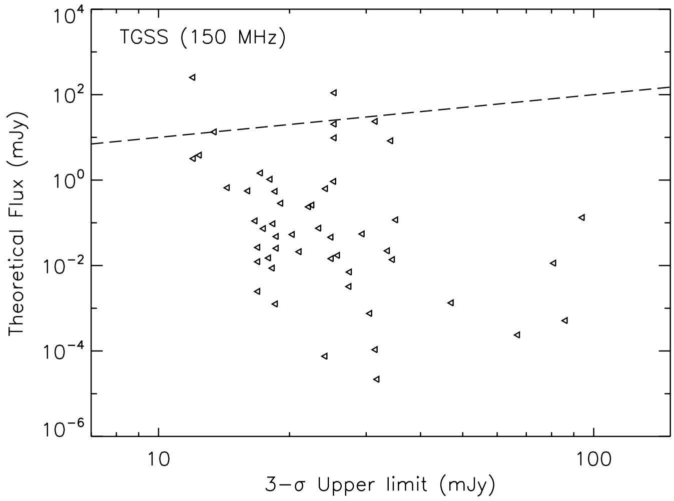

Fig. 3. Model predictions of flux density for the 51 known planets with orbital distances smaller than 0.1 au are plotted against their 3σ upper limit obtained from the TGSS. The dashed line shows the limit where the theoretical flux density equals the TGSS upper limit.

planet's flux density. We can apply this model to other planets with small orbital distances, using Eq. (17) of Jardine & Cameron (2008) and scaling the coronal electron density with orbital radius ($N_{\rm c} \propto R_{\rm orb}^{-1}$; Eq. (4) of Jardine & Cameron 2008). We thus find that the expected flux density of a planet orbiting within the stellar magnetosphere is

$$F = 41\ {\rm mJy} \left(\frac{N_{\rm c}}{N_{\odot}}\right)^2 \left(\frac{B_*}{40\ {\rm G}}\right)^{-2/3} \left(\frac{R_{\rm orb}}{0.03\ {\rm au}}\right)^{-1} \times \left(\frac{1{\rm day}}{P_{\rm orb}} - \frac{1{\rm day}}{P_*}\right)\left(\frac{d}{19.3\ {\rm pc}}\right)^{-2}, \quad (1)$$

where $N_{\rm c}$ is the coronal electron density of the planetary system's host star, B_* is the star's magnetic field, $R_{\rm orb}$ the orbital distance of the planet, $P_{\rm orb}$ its orbital period, P_* the rotation period of the star, and d is the distance to the planetary system (see Table 1). The 10% efficiency assumed here may be a large value compared to in situ measurements in the solar system (Lamy et al. 2011). If the efficiency is taken as 1%, then the resulting flux density given in Eq. (1) has to be reduced ten times.

We applied this relation to 55 Cnc e taking $P_* = 19$ days as derived from the star $v \sin i = 2.5$ km s^{-1}, and found a predicted flux density of 255 mJy. The apparent discrepancy with the non-detection (3σ upper limit of 28 mJy) can be interpreted in several ways. First, the planetary magnetic field can be below the value of 50 G needed for cyclotron emission at 150 MHz. Also, the Earth could be outside the planet's emission beam. Alternately, the stellar coronal density could be lower than 0.33 times the solar value. In any case, since planetary radio emissions are expected to be highly variable, new observations at the maximum available sensitivity are particularly recommended for this outstanding target.

2.3. The TGSS non-detections of hot planets

We applied Eq. (1) to the planetary systems undetected in the TGSS maps (Table 1), considering only the hot-planets with semi-major axis below 0.1 au for which this equation can be reasonably applied. Figure 3 shows a plot of the theoretical flux densities against the observed 3σ upper limits.

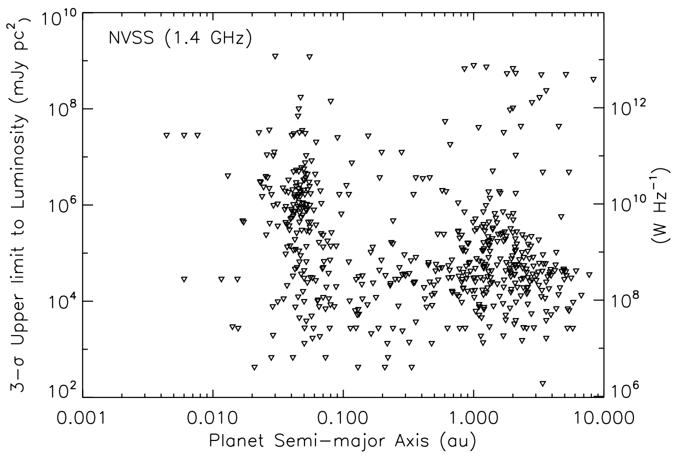

Fig. 4. Plot of the 3σ upper limits on the intrinsic 1.4 GHz radio luminosity (obtained using the NVSS) of 541 planets as a function of their semi-major axis.

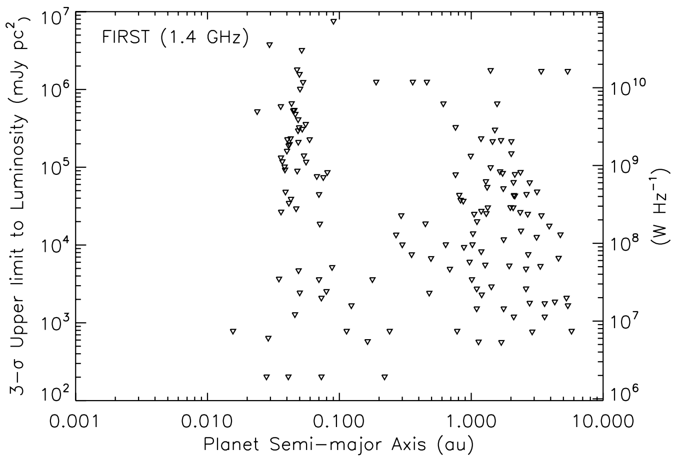

Fig. 5. Plot of the 3σ upper limits on the intrinsic 1.4 GHz radio luminosity (obtained using the FIRST survey) of 149 planets as a function of their semi-major axis.

It can be seen that about five hot-planets embedded within a stellar coronal density equal to the solar value can reach the TGSS detection threshold. In addition, for about 10 planets, a coronal density just 3 times higher than the solar value would push them above 3σ at 150 MHz. This allows us to be fairly optimistic about the prospect of detecting radio emission from hot exoplanets in the presently available maps of the TGSS, which cover about 10% of the full TGSS. When this survey is completed, the planetary systems in the TGSS sky coverage will be several times the present number of 175.

2.4. NVSS and FIRST non-detections

We have extended our search for radio emission from exoplanets by using the NVSS and the VLA FIRST survey. This has yielded 3σ upper limits for 565 and 139 planetary systems (harboring a total of 722 and 181 exoplanets) in the NVSS and the FIRST survey, respectively. As in Sect. 2.1 for the TGSS non-detections, we have converted the measured 3σ upper limits on the flux density into upper limits on the intrinsic 1.4 MHz radio-luminosity. These 3σ upper limits on the luminosity are plotted against the planets' orbital semi-major axis (Figs. 4 and 5). We infer that the typical 1.4 GHz radio-luminosity for these planetary systems must be below $\sim 10^4 - 10^5$ mJy pc^2, or $10^8 - 10^9$ W Hz^{-1}.

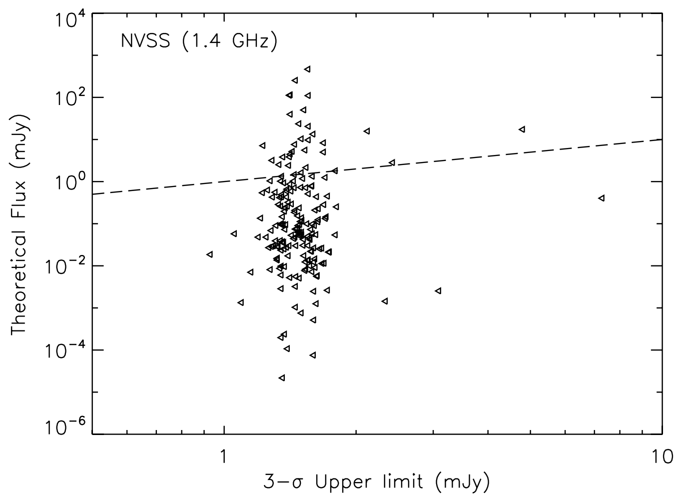

Fig. 6. Plot of the theoretically predicted flux density of the 194 known planets with orbital distance smaller than 0.1 au, compared to their 3σ upper limits obtained from the NVSS. The dashed line shows the limit where the theoretical flux density equals the NVSS upper limit.

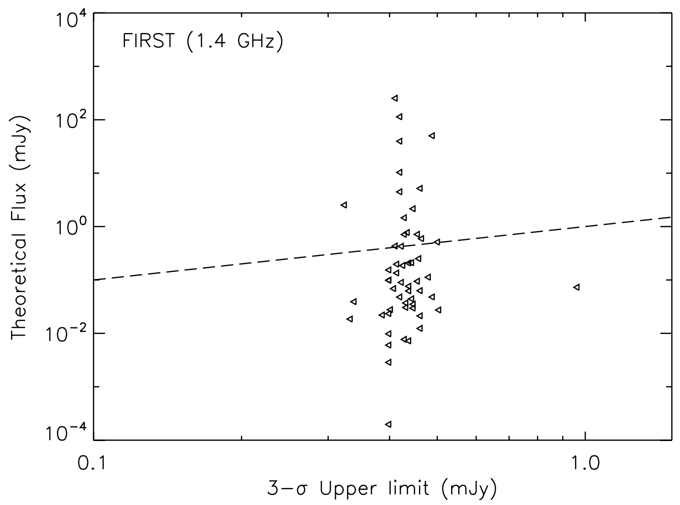

Fig. 7. Same as Fig. 6 where the 3σ upper limits (for 56 planets) are obtained from the VLA FIRST survey.

As in Sect. 2.3, we applied Eq. (1) to the planetary systems undetected in the NVSS and FIRST surveys, and that have at least a planet with a semi-major axis below 0.1 au. In Figs. 6 and 7 we plot the theoretical flux density against the observed 3σ upper limit. One can see that about 7 out of the 56 hot-planets embedded within the stellar corona with a density equal to the solar value should be detectable in the VLA FIRST maps. The prediction rises to 15 detectable hot-planets out of the 194 planetary systems covered in the NVSS maps. The discrepancy from the observations in both surveys might be resolved by invoking intrinsic variability and beaming of the emission, which could decrease drastically the probability of observing the radio emission. Nonetheless, the cause of the non-detections is more likely related to the high frequency of the NVSS and the FIRST survey. For cyclotron emission at 1.4 GHz the planetary magnetic field must be higher than ~500 G, a value 35 times the Jovian magnetic field.

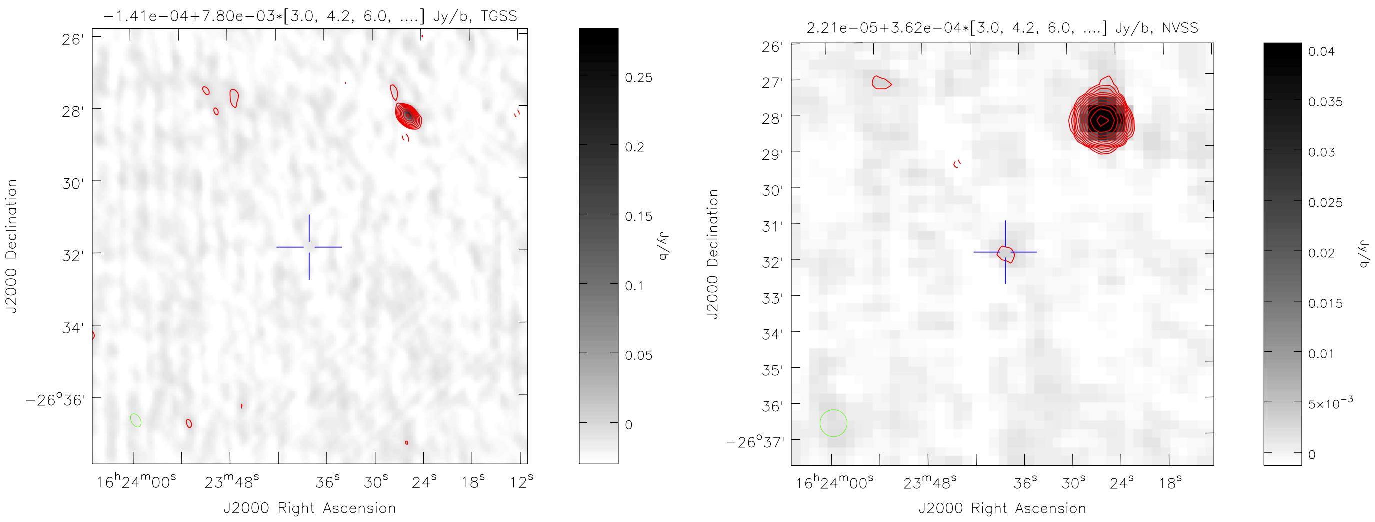

Fig. 8. TGSS (*left panel*) and NVSS images (*right panel*) of the PSR B1620-26 field at 150 MHz and 1.4 GHz. The green ellipse in the lower-left corner (of these images and other images presented in this paper) shows the half power beamwidth (∼20″for TGSS). The contour levels given at the top of the image (and other images presented in this paper) are in units of Jy beam^{-1} and are defined as mean+rms × (n), where n is given inside the brackets in the top label. Negative contours appear as dashed lines. The host star position is given by the blue cross. Here in the NVSS image the contour of the emission is well centered on that position.

3. Radio sources towards exoplanets

As mentioned in Sect. 2.1, by checking the TGSS maps in the directions of the 175 known extrasolar planetary systems, we have found four cases for which a source with a peak signal above 3σ lies within one beam-size from the position of the host star. Using the NVSS and the FIRST survey, we found additional radio sources coinciding with planetary systems, one using the NVSS and two using the FIRST survey. Below we discuss all seven of these systems.

3.1. PSR B1620-26

The source PSR B1620-26 (α = 16h23m38s, $\delta = -26°31'54''$, J2000) is a known millisecond pulsar with a triplet system within the globular cluster M4 located about 3800 pc away. Pulse timing ($\Omega_* = 567\,\mathrm{s}^{-1}$) data have revealed a planet of about 2.5 Jupiter mass orbiting at about 23 au from the neutron star (Backer et al. 1993; Thorsett et al. 1993), whose mass is estimated to be 1.35 $M_\odot$ (Thorsett et al. 1999; Sigurdsson et al. 2003).

The NVSS map shows a radio source at the coordinates of PSR B1620-26, with a flux density of 1.5 ± 0.36 mJy at 1.4 GHz (Fig. 8). However, the source is only marginally detected in the TGSS, with a flux density of 14.2 ± 7.8 mJy. The pulsar spectral index then is $\alpha > -1$ between 150 MHz and 1.4 GHz.

Recently, the possibility of radio emission from planets orbiting around pulsars has been discussed (Mottez 2011; Mottez & Heyvaerts 2011). This emission does not come from the planet itself, but from the Alfvén wings extending all along the planetary orbit embedded within the pulsar wind. A fraction of the power emitted by the star through magnetic dipole radiation is captured and heats the planet, generating current and radio emission (Mottez & Heyvaerts 2011).

At present, very limited information is available, particularly on the emission's pulsation rate and so, it is difficult to unambiguously establish the origin of the detected radio emission. The radio counterpart detected in the NVSS can be related either to the pulsar, or to the planet itself. Further observations are required to discriminate between these alternatives.

3.2. 61 Vir

The G5V main-sequence star 61 Vir (alias HD 5019 and HD 115617) is orbited by at least a triplet of planets: one super-Earth and two Neptune-mass planets of 5, 18, and 24 Earth mass, respectively: 61 Vir b, 61 Vir c, and 61 Vir d (Vogt et al. 2010). These planets are all in low-eccentricity orbits with periods of 4.2, 38.0, and 124.0 days. The system lies at a small distance of 8.5 pc (Perryman et al. 1997).

The TGSS map shows an elongated radio source about 1′ in size and the proper motion corrected position of the star hosting the planetary system falls within 3.2″ from the radio peak detected at about 13σ (Fig. 9). The distance of <4″ is well within the positional uncertainty of the TGSS. The same radio source is also clearly seen in the NVSS map.

It is noteworthy that 61 Vir (also named LHS 349) appears very high (5th position) in the list published by Nichols (2012) of the top ten potential exoplanetary systems for observing internally generated exoplanetary emission. The radio source flux density predicted in Nichols (2012) is in the range 0.07–40 mJy, significantly lower than the observed peak flux toward 61 Vir above 120 mJy at 150 MHz. However, many uncertainties remain on the model inputs (e.g., the planetary angular velocity and the dynamic pressure), and this shows that strong radio emission from the planetary system of 61 Vir is plausible. Our observations make this object a particularly interesting target for further radio observations.

Although we cannot yet confirm or exclude the possibility of the radio emission being associated with the planetary system, a higher resolution radio map would help in checking if it is merely a chance projection of a background radio source close to the star's direction, or emission coming from the planetary system itself.

3.3. HD 86226

The giant planet HD 86226 b was discovered in the Magellan Planet Search Program (Arriagada et al. 2010). It orbits a solar metallicity G2 dwarf star located at a distance of 45.0 ± 1.6 pc from the Sun in the Hydra constellation. The star has a rotation

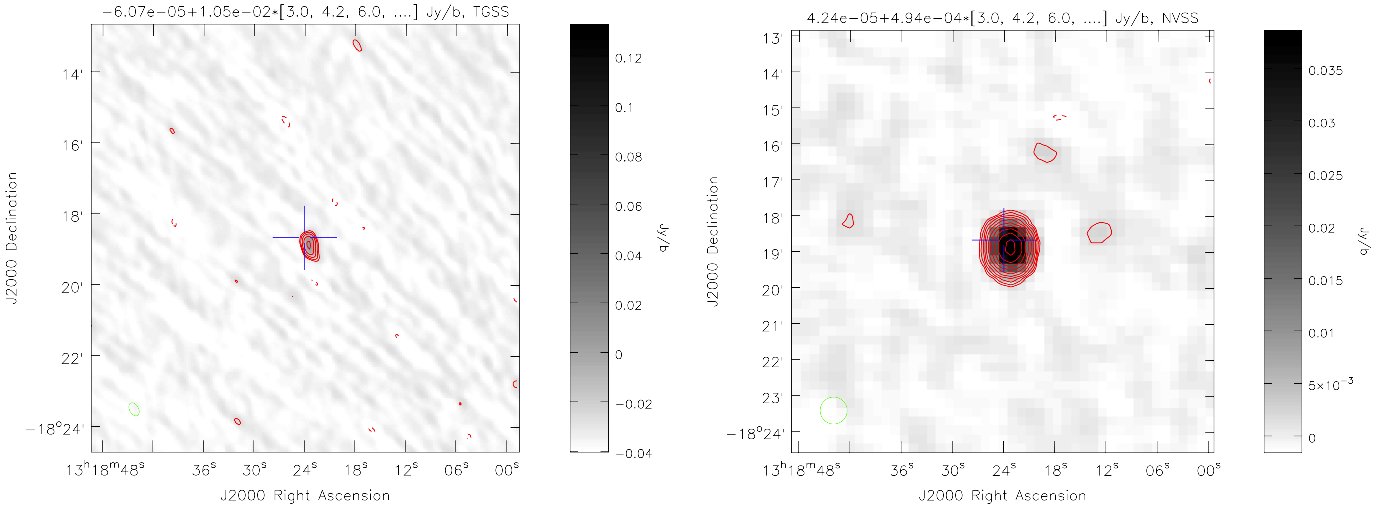

Fig. 9. TGSS (*left panel*) and NVSS images (*right panel*) of the 61 Vir field at 150 MHz and 1.4 GHz.

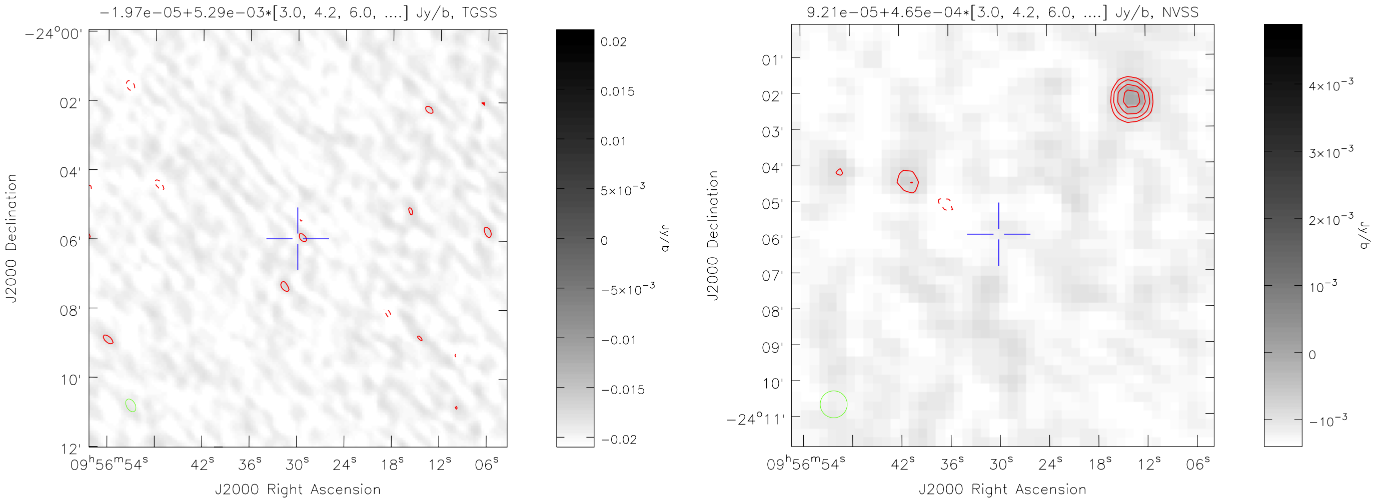

Fig. 10. TGSS (*left panel*) and NVSS images (*right panel*) of the HD 86226 field at 150 MHz and 1.4 GHz. In the TGSS image the 3σ contour of the emission is about 7″ west from the position of the planet host star (blue cross).

period of 23 ± 4 days (Marmier et al. 2013). The CORALIE measurements covering 11 years of observations confirm the companion to be a Jupiter-like planet with a minimum mass $M_p \sin i = 0.92 \pm 0.10$ Jupiter mass, and an orbital period of 4.6 years corresponding to a semi-major axis of 2.84 ± 0.06 au (Marmier et al. 2013).

All the characteristics of this planet resemble a Jupiter-like planet. Given its distance of 45 pc, HD 86226 b is not at the top of the list of the targets for which detection at radio-wavelengths can be expected with existing facilities. However, a 3σ peak of 19 mJy is detected at about 7″ from the star coordinates in the TGSS map (Fig. 10). This distance is well below the uncertainty on the position on TGSS map (about 9″ for a 3σ source if we take systematic errors into account). Therefore, the TGSS source can be the central star or the planet (both have a separation of 0.065″). If one considers the star-planet interaction, HD 86226 b appears to lack the extreme characteristics believed to be necessary for a radio detection. As noted for 61 Vir, radio emission can be strong enough to be detected if the planet is rotating rapidly. There are still many unknowns that could make this object radio-loud, e.g., the presence of a massive satellite, or an extremely strong planetary magnetic field. Deeper radio observations toward HD 86226 are needed to discriminate between a possible background radio source and an exotic radio-loud planet.

3.4. 1RXS1609 b

The source 1RXS1609.1−210524 is a pre-main-sequence star, a young solar analog (about one solar mass) within the 5 Myr old Upper Scorpius stellar association. Direct imaging has revealed a ~8 Jupiter-mass object orbiting at 2.2″ (330 au) from the parent star (Lafrenière et al. 2008). Because of its young age, the companion has a temperature of 1800 ± 200 K (Lafrenière et al. 2010). The large orbital distance of the planet, amounting to several hundred astronomical units, poses a serious challenge to current models of planet formation. Nonetheless, recent analysis of star-formation history in the Upper Scorpius association led to an older estimate of ~11 Myr for the mean age; subsequently, the mass of the companion was re-estimated as 14 Jupiter mass, possibly arguing that the companion should more likely be classified as a low-mass brown dwarf, rather than a planet (Pecaut et al. 2012).

The TGSS map shows a rather strong point source at about 8″ from 1RXS1609.1−210524 (Fig. 11), with a flux density of 28 ± 4.5 mJy at 150 MHz; the source is detected at about 6.2σ. It is also seen in the NVSS map, with a flux density of 5 ± 0.5 mJy at 1.4 GHz. Its spectral index is thus about $\alpha = -0.77$, between 150 MHz and 1.4 GHz.

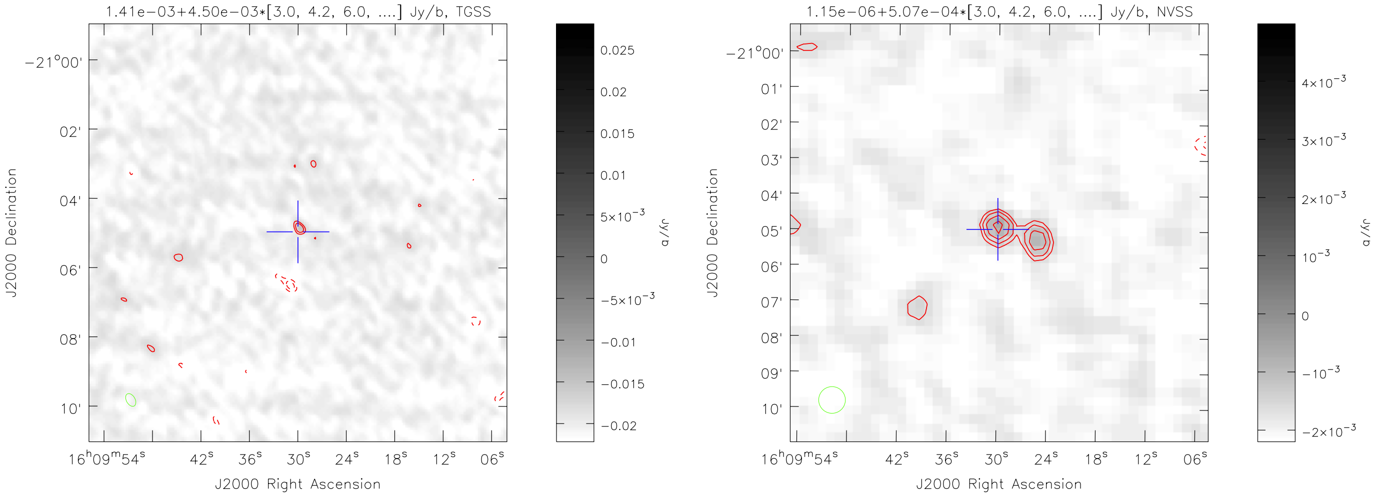

Fig. 11. TGSS (*left panel*) and NVSS images (*right panel*) of the 1RXS1609 field at 150 MHz and 1.4 GHz.

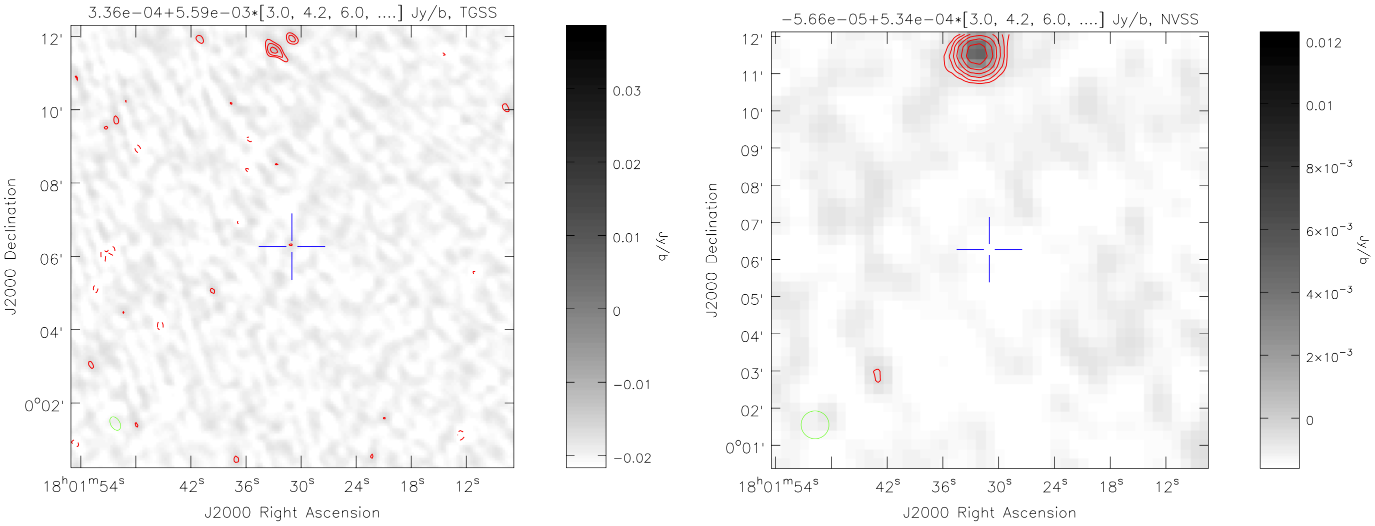

Fig. 12. TGSS (*left panel*) and NVSS images (*right panel*) of the HD 164509 field at 150 MHz and 1.4 GHz with the same legend as in Fig. 8. In the TGSS image the 3σ contour is seen as a tiny dot of emission, which is well centered on the position of the planet host star (blue cross).

Bearing in mind that radio emissions have been detected from pre-main-sequence stars and the possibility of the companion being a young brown dwarf (located at a larger distance from its host star), it is difficult to come to a conclusion about the origin of the radio counterpart seen in the TGSS map. Moreover, flaring radio emissions from a cool (~900 K) brown dwarf have been detected with the Arecibo telescope at 4.75 GHz (Route & Wolszczan 2012). Therefore, the present case of a 14 Jupiter mass companion to a pre-main-sequence star appears to be extremely interesting.

Moreover, although 1RXS1609 b is more distant than the stars considered by Nichols (2012), it has all the elements required to be an excellent target for rotation-induced radio emissions: this system possesses a star with high X-ray-UV luminosity which is favorable for generating high ionospheric conductance, a planet with a large orbital distance (favoring a physically large magnetosphere), and a high mass (presumably favoring a large dipole moment). In the framework of the Nichols models (see also Nichols et al. 2012), all these properties are likely to lead to large-amplitude currents and therefore high radio power.

Good prospects for comparison are presented by the recent discovery of a giant planet orbiting another solar-type star

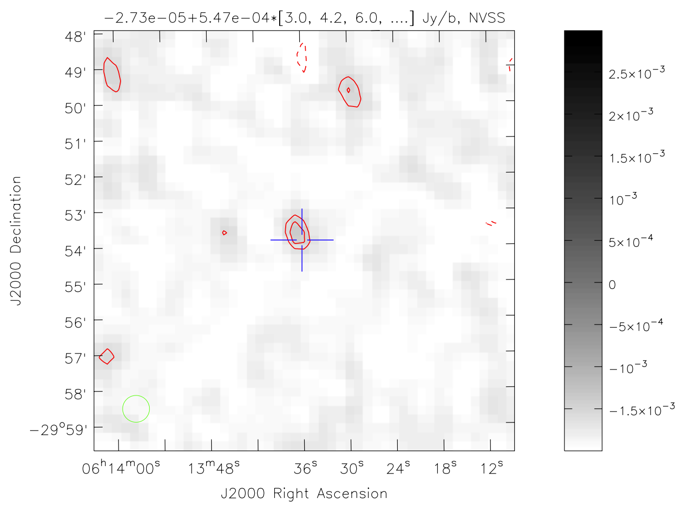

Fig. 13. NVSS image of HD 43197 at 1.4 GHz. Same legend as in Fig. 8.

in the same Upper Scorpius association (GSC 06214−00210b; Ireland et al. 2011; Bowler et al. 2011), with a mass of about 14 Jupiter mass and orbiting at about 300 au. Further

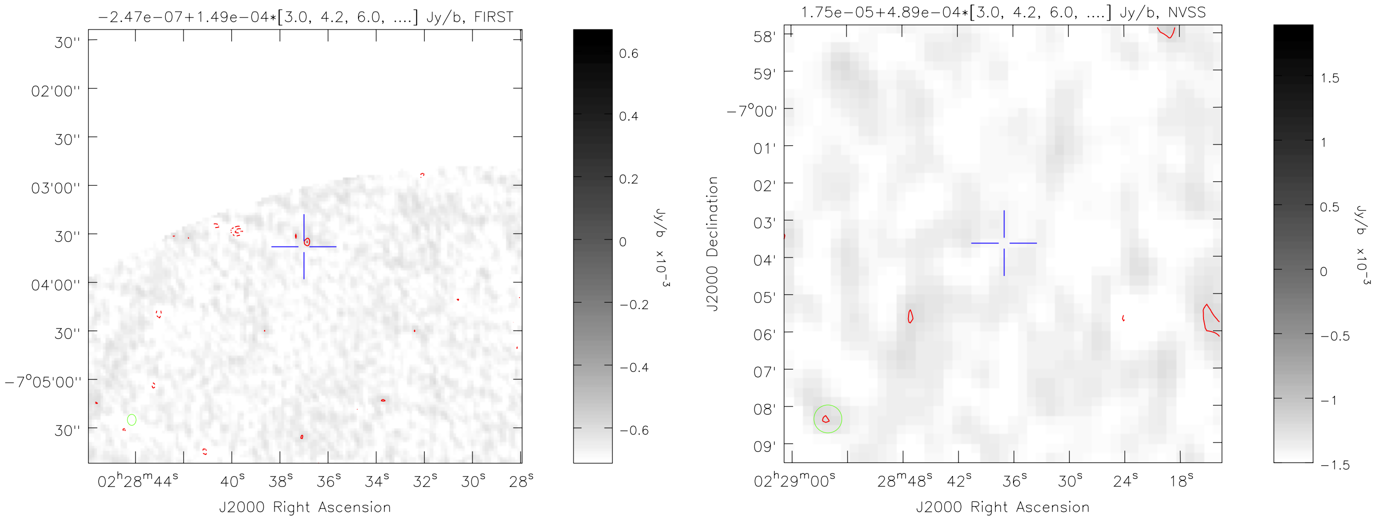

Fig. 14. FIRST (*left panel*) and NVSS (*right panel*) images of the WASP-77A field at 1.4 GHz. Same legend as in Fig. 8. A source in the FIRST image is drawn by two contours located at 7″ north-west from the WASP-77A position (blue cross).

observations of these systems at radio wavelengths are strongly encouraged.

3.5. HD 164509

The G5V star HD 164509 is metal-rich ([Fe/H] = 0.21) and is located at a distance of 52 pc; it has a 0.48 ± 0.09 Jupiter mass planet orbiting in 282.4 ± 3.8 days. The orbit has a semi-major axis of 0.875 ± 0.008 au and an eccentricity of 0.26 ± 0.14 (Giguere et al. 2012).

The TGSS map shows a barely detected radio source with a flux of 18 ± 6 mJy (seen as a tiny dot in the contour plot of Fig. 12). Moreover, the coincidence of the source with a side-lobe pattern found in the map make this detection even more marginal. Once again, deeper observations at 150 MHz are needed to draw any conclusion from this case.

3.6. HD 43197

The extrasolar planet HD 43197 b is a giant planet in a highly eccentric orbit (e = 0.83), discovered by radial velocity measurements using the HARPS spectrograph (Naef et al. 2010). Orbiting a G8V star ($M_\star$ = 0.96 $M_\odot$) of high metallicity ([Fe/H] = 0.40 ± 0.04), the planet's minimum mass is 0.6 $M_{\rm Jup}$. The orbital semi-major axis is 0.92 au. The system is located at a distance of $56.3^{+4.2}_{-3.6}$ pc.

Only an NVSS map is available for this system (Fig. 13), where a peak source of 3 ± 0.5 mJy is seen. With such extreme orbital eccentricity, and a periastron of only 0.16 au, this target is definitly an exotic planet, and warrants observations at longer radio-wavelengths.

3.7. WASP-77A b

The discovery of the transiting planet WASP-77A b in the frame of the Wide Angle Search for Planets (WASP) has been reported very recently by Maxted et al. (2013). With an orbital period of 1.36 days, the planet orbits the brighter component of the visual binary star BD -07°436. The host star, WASP-77A, is a G8V star with a mass and metallicity close to solar ([Fe/H] = 0.0 ± 0.1). The 1.76 ± 0.06 Jupiter mass planet has a radius of 1.21 ± 0.02 Jupiter radius.

With its very short orbital semi-major axis, this giant planet belongs to the very-hot-Jupiter category, and is therefore a prime target for radio emission search. Here we report the detection of a source of 0.67 ± 0.15 mJy at 1.4 GHz in the FIRST survey (Fig. 13). The source is located at about 7″ from the star coordinates. Therefore Wasp-77 also merits observations at longer radio wavelengths.

4. Discussion

To recapitulate, we have searched for radio emission from 175 extrasolar planets at 150 MHz using the TGSS DR5 data products. No radio counterparts were found for 171 of the planetary systems. According to theoretical and observational aspects of the radio emission from extrasolar planets, as discussed in Zarka (2007) where the generalized concept of flow-obstacle interaction is developed, the present non-detections may be understood in terms of the following possibilities: (1) the Earth was outside the planet's emission beam at the time of observation; (2) the radio emission is highly variable; (3) the planetary radio emission is intrinsically too weak, or perhaps in most cases; (4) the planetary emission peaks at frequencies lower than 150 MHz because of a weaker planetary magnetic field.

Nonetheless, we have identified 7 planetary systems for which radio emissions are detected in the TGSS and/or the NVSS/FIRST survey maps based on positional coincidence. Each case appears to be different from the others and further observations are needed to understand their nature reliably.

For 61 Vir, the extended radio source seen at 150 MHz may eventually turn out to be a background source, possibly a distant radiogalaxy. However, it is noteworthy that for this system a large radio flux density was predicted in the scenario involving magnetosphere-ionosphere coupling and rotation-induced radio emission (Nichols 2012).

We also found 150 MHz emissions toward HD 86226 and HD 164509, two stars harboring giant gaseous planets on moderately eccentric orbits with semi-major axes of 2.84 au and 0.875 au, respectively. Again, strong radio emission can be produced by the presence of a massive satellite orbiting a rapidly rotating planet. There are still many unknowns that could make these objects radio-loud. Additional deeper observations toward these two planetary systems are needed to discriminate between the possibilities of background radio-sources and radio-loud exoplanets.

We detected 150 MHz emission toward 1RXS1609 b, a pre-main-sequence star harboring a ~14 Jupiter mass planet, or a brown dwarf, at a separation of about 330 AU from the host star. With a bright X-ray-UV star and a high mass, the planet 1RXS1609 b presents the best characteristics for rotation-induced emissions with high radio power. Further radio observations of this system are especially encouraged.

For the pulsar PSR B1620-26, the detected 1.4 GHz emission can arise from the neutron star itself. However, scenarios where radio emission is caused by a giant planet through Alfvén wings within the pulsar wind have also been proposed. Lastly, emissions at 1.4 GHz are also detected toward two exotic planets: the very-hot-Jupiter WASP-77A b (FIRST survey) and the giant planet HD 43197 b with an orbital eccentricity (NVSS).

The scope of the present work is not to come to a conclusion about the nature and origin of the detected radio emissions. We only want to identify the most promising candidates for detailed observations at radio wavelengths. The TGSS survey at 150 MHz is proving effective in identifying promising exoplanets for low-frequency radio observations.

Acknowledgements. This work is based on observations made with the Giant Metrewave Radio Telescope, which is operated by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research and is located at Khodad, Maharashtra, India. We warmly thank the GMRT staff for the efficient support to these observations. One of us (AL) would like to thank the Director, IUCAA for supporting a visit to IUCAA, during which part of this work was done. This work has been supported by the award of the Fondation Simone et Cino Del Duca. The authors also acknowledge the support of the French Agence Nationale de la Recherche (ANR), under program ANR-12-BS05-0012 Exo-Atmos.

References

Arriagada, P., Butler, R. P., Minniti, D., et al. 2010, ApJ, 711, 1229
Backer, D. C., Foster, R. S., & Sallmen, S. 1993, Nature, 365, 817
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Bowler, B. P., Liu, M. C., Kraus, A. L., Mann, A. W., & Ireland, M. J. 2011, ApJ, 743, 148
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Dawson, R. I., & Fabrycky, D. C. 2010, ApJ, 722, 937
Ehrenreich, D., Bourrier, V., Bonfils, X., et al. 2012, A&A, 547, A18
Giguere, M. J., Fischer, D. A., Howard, A. W., et al. 2012, ApJ, 744, 4
Griessmeier, J.-M., Zarka, P., & Spreeuw, H. 2007, A&A, 475, 359
Hallinan, G., Sirothia, S. K., Antonova, A., et al. 2013, ApJ, 762, 34
Ireland, M. J., Kraus, A., Martinache, F., Law, N., & Hillenbrand, L. A. 2011, ApJ, 726, 113
Jardine, M., & Cameron, A. C. 2008, A&A, 490, 843
Lafrenière, D., Jayawardhana, R., & van Kerkwijk, M. H. 2008, ApJ, 689, L153
Lafrenière, D., Jayawardhana, R., & van Kerkwijk, M. H. 2010, ApJ, 719, 497
Lamy, L., Cecconi, B., Zarka, P., et al. 2011, J. Geophys. Res., 116, 4212
Lazio, T. J. W., & Farrell, W. M. 2007, ApJ, 668, 1182
Lazio, J., Bastian, T., Bryden, G., et al. 2009, Astro2010: The Astronomy and Astrophysics Decadal Survey (Science White Papers), 177 [arXiv:0903.0873]
Lecavelier des Etangs, A., Sirothia, S. K., Gopal-Krishna, & Zarka, P. 2009, A&A, 500, L51
Lecavelier des Etangs, A., Sirothia, S. K., Gopal-Krishna, & Zarka, P. 2011, A&A, 533, A50
Lecavelier des Etangs, A., Sirothia, S. K., Gopal-Krishna, & Zarka, P. 2013, A&A, 552, A65
Marmier, M., Ségransan, D., Udry, S., et al. 2013, A&A, 551, A90
Maxted, P. F. L., Anderson, D. R., Collier Cameron, A., et al. 2013, PASP, 125, 48
Mottez, F. 2011, in Proc. 7th Int. Workshop on Planetary, Solar and Heliospheric Radio Emissions (PRE VII), 315
Mottez, F., & Heyvaerts, J. 2011, A&A, 532, A21
Moutou, C., Donati, J.-F., Savalle, R., et al. 2007, A&A, 473, 651
Naef, D., Mayor, M., Lo Curto, G., et al. 2010, A&A, 523, A15
Nichols, J. D. 2011, MNRAS, 414, 2125
Nichols, J. D. 2012, MNRAS, 427, L75
Nichols, J. D., Burleigh, M. R., Casewell, S. L., et al. 2012, ApJ, 760, 59
Pecaut, M. J., Mamajek, E. E., & Bubar, E. J. 2012, ApJ, 746, 154
Perryman, M. A. C., Lindegren, L., Kovalevsky, J., et al. 1997, A&A, 323, L49
Sigurdsson, S., Richer, H. B., Hansen, B. M., Stairs, I. H., & Thorsett, S. E. 2003, Science, 301, 193
Swarup, G. 1990, Indian Journal of Radio and Space Physics, 19, 493
Thorsett, S. E., Arzoumanian, Z., & Taylor, J. H. 1993, ApJ, 412, L33
Thorsett, S. E., Arzoumanian, Z., Camilo, F., & Lyne, A. G. 1999, ApJ, 523, 763
Vogt, S. S., Wittenmyer, R. A., Butler, R. P., et al. 2010, ApJ, 708, 1366
Zarka, P. 2007, Planet. Space Sci., 55, 598
Zarka, P. 2011, in Planetary Radio Emissions VII, eds. H. O. Rucker et al. (Vienna: Austrian Acad. Sci. Press), 287