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Searching for low mass objects around nearby dMe radio stars

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Abstract.
Nearby M-dwarfs are best suited for searches of low mass companions. VLBI phase-referencing observations with sensitive telescopes are able to detect radio star flux-densities of tenths of mJy as well as to position the star on the sky with submilliarcsecond precision. We have initiated a long-term observational program, using EVN telescopes in combination with NASA DSN dishes, to revisit the kinematics of nearby, single M dwarfs. The precision of the astrometry allows us to search for possible companions with masses down to 1 Jupiter mass. In this contribution we report preliminary results of the first observation epochs, in which we could detect some of the radio stars included in our program.

1. Introduction

In the last years, optical spectroscopy techniques have shown to be extraordinarily effective in detecting very low mass objects around nearby stars. However, astrometric techniques still offer two extra advantages: first, the determination of the mass of the companion without coupling with the orbit inclination, and second, the detection of companions with longer periods and larger distances from the host star than those typical of the orbits detected by spectroscopy (that is, orbits similar to the ones known in our solar system). In particular, submilliarcsecond VLBI astrometry has demonstrated its capabilities for more than two decades.

VLBI phase-referencing allows the detection of weak radio sources, with flux densities smaller than the sensitivity limit imposed by the fluctuations of the atmosphere and the frequency standard at each VLBI site. A reference for the VLBI phase must be established by interleaving observations of an angularly nearby strong extragalactic source. This cyclic observing scheme effectively allows to increase the coherent integration time on the target (weak) source from minutes to hours, with the corresponding improvement of the sensitivity. In addition, since the main observable used is the interferometric phase, this technique provides high-precision relative position information of the two observed sources.

Among the stellar objects potentially detectable with VLBI phase-referencing, nearby, single radio-emitting stars are best suited for astrometric searches for low-mass stellar companions. In particular, nearby M-dwarfs are very good candidates: they are close to the Sun ($\sim$5 pc), and they have very low inertia (M$\sim$0.3 $M_\odot$, for a main-sequence M5 dwarf) which, according to the Kepler's third law, implies a large reflex motion for a given orbiting low-mass companion. In addition to this, many M dwarfs exhibit non-thermal, compact radio emission consisting of a slowly varying quiescent flux that may increase by an order of magnitude when the star is flaring.

We have initiated a long-term VLBI astrometric program to observe a sample of nearby dMe stars. The goal of this program is to refine the kinematics of nearby radio stars to uncover possible reflex motions resulting from the gravitational interaction of unseen low mass companions. From the very active, well-known flare M dwarfs, we have selected those placed around 10pc from the Sun, detected previously at least with the VLA at a flux density of 1 mJy or more (see Table 1). Some of them have already been detected with VLBI arrays: AD Leo, YZ CMi (Pestalozzi et al. 2000 and references therein), EQ Peg B (Benz et al 1995), Wolf 630 A, and EV Lac (Phillips et al. 1989). In our sample there are both single stars (EV Lac, YZ CMi, AD Leo, and Wolf 47), already included in ongoing planetary searches in the visible and infrared, and wide-separation binaries, with the partner star placed a few arcseconds away (3" and 5" for DO Cep and EQ Peg B, respectively). In the latter case, the gravitational interaction produces a long-term orbital motion that should be disentangled easily from the possible reflex wobble corresponding to another companion. In this contribution, we report the first detections of radio stars included in our sample. Despite of the preliminary astrometric analysis, these detections show the feasibility of our program to detect companions down to 1 Jupiter mass.

2. Observations and Data Reduction

We made VLBI phase-referenced observations of dMe stars at 8.4 GHz at multiple epochs (see Table 2) with EVN antennas along with the 70m DSN dishes in Madrid (DSS63) and Goldstone (DSS14). For each experiment, we interleaved observations of a strong background radio source. The data were correlated with the Mark III/IV correlator at the MPIfR in Bonn. For each epoch and ra-

Table 1. Radio stars included in our program

	Distance (pc)	Quiescent [a] emission (mJy)	Reference [b] source
Wolf 47	9.3	<0.3 - 7.1	0059+581 (3.6°)
YZ CMi	6.1	0.6 - 1.5	0736+017 (2.4°)
AD Leo	4.9	0.2 - 2.1	1022+194 (1.4°)
DO Cep	4.0	<0.4 - 5.5	2250+555 (3.1°)
EV Lac	5.1	<0.3 - 4.0	2253+417 (2.8°)
Wolf 630 A	6.2	<2.0 - 4.0	1741−038 (5.5°)
EQ Peg B	6.6	1.1 - 5.5	J2341+19 (2.2°)

[a]: Slowly varying quiescent, non-flare emission at cm-wavelengths (taken from Caillault et al. 1988; Fomalont & Sanders 1989; Phillips et al. 1989; White et al. 1989; Benz & Alef 1991; Benz et al. 1995; Leto et al. 2000). [b]: Radio sources selected to act as reference sources in the phase-reference mapping analysis. Separation from the corresponding radio stars in parentheses.

dio star, we derived a priori (correlation) coordinates from the data given in the Hipparcos catalogue (ESA 1997). We corrected these coordinates for proper motion and trigonometric parallax effects from a reference epoch (1991.25 for the Hipparcos catalogue) to the epoch of our observations. For each experiment, we performed a phase-calibration analysis within AIPS (Beasley & Conway 1995). The resulting referenced phases of the radio stars show the corrections of the a priori relative coordinates. We determined these corrections by inspection of the phase-reference map of the radio star, constructed by Fourier inversion of its (referenced) visibilities.

The sensitivity of our array is largely dominated by the performance of the baseline DSS63-Bonn. The use of short arrays for radio star astrometry was proved to be successful: with a similar array (DSS43–Hobart) the kinematics of some southern radio stars was monitored to the the precision of a tenth of milliarcsecond. The precision and consistency of those data allowed even the detection of a previously unseen low-mass object around the star AB Doradus (Guirado et al. 1997). For comparison, the baseline DSS63–Bonn provides similar precision in the astrometry (∼0.3 mas in the determination of the relative positions) and far more sensitivity (threshold sensitivity of 0.4 mJy at 8.4 GHz, corresponding to 7σ for 5 hours integration time and 56 MHz bandwidth).

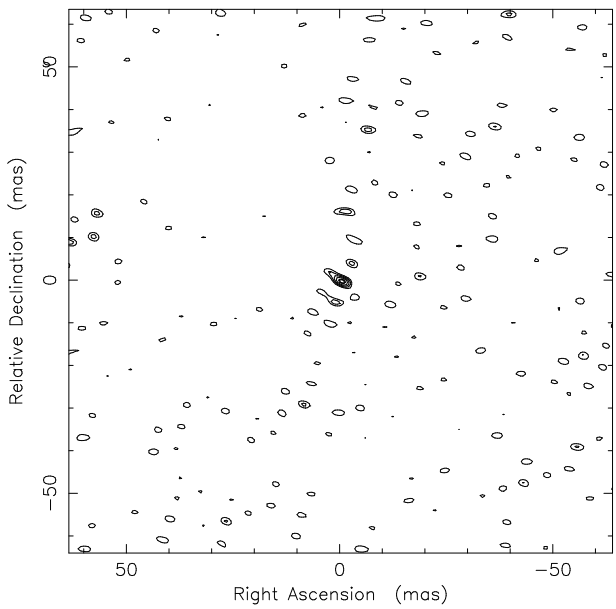

Fig. 1. Phase-referenced (dirty) map of EQ Peg B. The offset of the brightness maximum from the map center corresponds to the error in the a priori coordinates of EQ Peg B relative to 2337+220. Contours are 30, 45, 60, 75, 90, and 95% of the peak of brightness. The restoring beam is an elliptical Gaussian of 3.8×2.3 mas (P.A. 86°).

3. Results and Discussion

We have analyzed the first three epochs shown in Table 2. We did detect EQ Peg B at epoch 1996.82, and EV Lac and Wolf 47 at epoch 1999.76. We failed to detect any of the stars observed at epoch 1999.64. In what follows, we give for each source some notes:

3.1. EQ Peg B

This star is a dM6e main-sequence star at a distance of 6.6 pc (see Table 1), actually part of a wide-separation binary system with the partner star placed at ∼5". EQ Peg B has been detected at 18cm with intercontinental baselines (Benz et al. 1995). We have detected this star at our first epoch at the level of 2.8 mJy, that is more than 10 times the theoretical root-mean-square (rms) noise level. The phase-referenced map of EQ Peg B is displayed in Fig. 1; for each coordinate, the peak of brightness is shifted less than 1 milliarcsecond (mas) with respect to a priori position.

3.2. EV Lac

This single star is a well-known dM4.5e radio star at a distance of 5.1 pc (see Table 1). EV Lac is a traditional target in planetary searches carried out through radial velocity measurements, infrared observations, or optical astrometry. This object is a usual target in stellar radio astronomy: it has been detected several times with the VLA

Table 2. Radio star VLBI observations

Obs. Date	Stations	Stars observed
28-Oct-1996 (1996.82)	Bonn, DSS65, Onsala, Noto	EQ Peg B
21-Aug-1999 (1999.64)	Bonn, DSS63, DSS14	Wolf 47, DO Cep, EV Lac
6-Oct-1999 (1999.76)	Bonn, DSS63	Wolf 47, EV Lac
11-Dec-1999 (1999.94)	Bonn, DSS63	AD Leo, DO Cep, EQ Peg B
8-Jan-2000 (2000.02)	Bonn, DSS63	AD Leo
4-Jul-2000 (2000.50)	Bonn, DSS63	DO Cep, EV Lac
5-Feb-2001 (2001.10)	Bonn, DSS63, DSS14	DO Cep, EV Lac

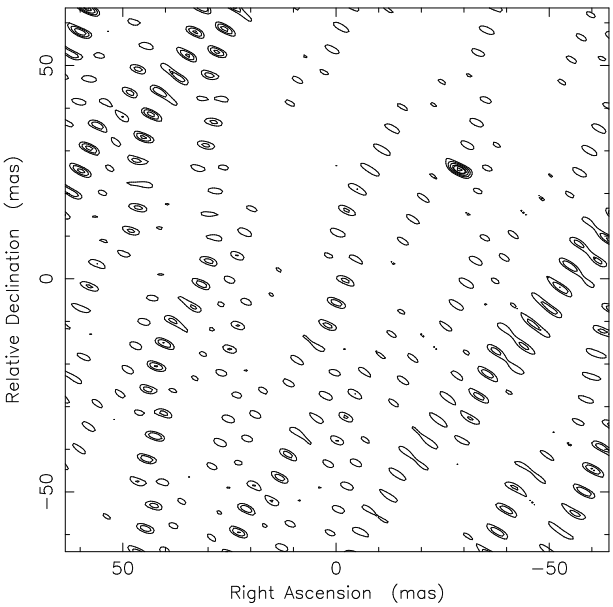

Fig. 2. Phase-referenced (dirty) map of EV Lac. The offset of the brightness maximum from the map center corresponds to the error in the a priori coordinates of EV Lac relative to 2253+417. Contours are 30, 45, 60, 75, 90, and 95% of the peak of brightness. The restoring beam is an elliptical Gaussian of 5.6×2.0 mas (PA 69°).

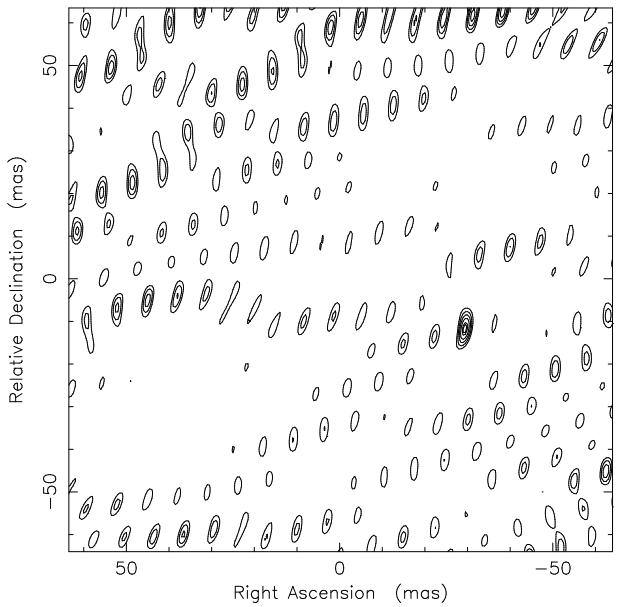

Fig. 3. Phase-referenced (dirty) map of Wolf 47. The offset of the brightness maximum from the map center corresponds to the error in the a priori coordinates of Wolf 47 relative to 0059+581. Contours are 30, 45, 60, 75, 90, and 95% of the peak of brightness. The restoring beam is an elliptical Gaussian of 6.3×2.4 mas (PA -11°).

(White et al. 1989, Leto et al. 2000), and an early detection with VLBI arrays (actually using the Bonn-DSS63 baseline) was reported by Phillips et al. (1989), with a flux density of 2-4 mJy. We have detected EV Lac in at our third epoch (1999.76) at the level of 3 mJy, that is ∼30 times the theoretical rms noise level. The phase-referenced map of EV Lac is displayed in Fig. 2; the peak of brightness is shifted −29 mas in right ascension and 25 mas in declination.

3.3. Wolf 47

This star is a dM5e radio star at a distance of 9.3 pc (see Table 1). Wolf 47 has been detected several times with the VLA at 8.4 GHz (Hewitt et al. 1989) and at longer wavelengths (White et al. 1989). Although it was proposed as a promising VLBI target (Hewitt et al. 1989), there is not any reported attempt to observe this radio star with VLBI. Hence, our detection of Wolf 47, with a flux density of 2.2 mJy, ∼20 times the theoretical rms noise level, happens to be the first one with VLBI. The phase-referenced map of EV Lac is displayed in Fig. 3; the peak of brightness is shifted −30 mas in right ascension and −11 mas in declination.

The phase-referenced maps shown in Figs. 1-3 were derived from the Fourier inversion of the referenced visibilities, which relied solely on the MkIII correlator astrometric model. Although the astrometric analysis is still underway, the large correction from the a priori position of some of the detected radio stars can be justified by the large standard deviation of the a priori positions (standard deviation dominated by the contribution of the error in the proper motion measurement, which scales by the ∼8-years time interval between the Hipparcos reference date and the epoch of our observations), and to a lesser extent, to the lack of atmospheric correction in our pre-

liminary astrometric analysis. These latter effects are partially canceled by the proximity of the background radio source to the radio star on the sky, and they are unlikely to contribute more than a few milliarcseconds.

Finally, a word on the expected precision of our astrometric program. We expect that fluctuating error will dominate the standard deviation of the relative position of the radio star. Among these errors, instabilities of the star's surface are most important since they may change the reference point selected for the astrometry randomly from epoch to epoch. On this respect we notice that i) the size of the photosphere of the proposed stars ranges from 0.2 to 0.8 mas (White et al. 1989; Delfosse et al. 1998) about the order of magnitude of the expected precision of our determination; and ii) the motion of the hot spots may not have a given trend, therefore it is expected to be averaged out from our data after several epochs. Thus, our initial goal to detect orbital motions of $\sim$1 mas amplitude should still be achievable with our VLBI-based search, enough precision to detect companions with masses as low as 1 Jupiter mass in less than four years.

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