Detection of continuum radio emission associated with Geminga

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ABSTRACT

A deep Very Large Array observation of the Geminga pulsar field led to the discovery, at a higher than 10σ significance level, of radio emission trailing the neutron star proper motion. This ∼10′′-long radio feature, detected with a flux of ∼0.4 mJy at 4.8 GHz, is marginally displaced (2.7 ± 1.8 arcsec) from the pulsar (which, at any rate, is unlikely to contribute with magnetospheric pulsed emission more than 15% to the total observed radio luminosity, ∼10^{29} \text{erg s}^{-1}) and positionally coincident with the X-ray axial tail recently discovered by Chandra and ascribed to the pulsar wind nebula (PWN). Overall, the Geminga radio tail is compatible with the scenario of a synchrotron-emitting PWN, but the present data do not allow us to discriminate between different (and not always necessarily mutually exclusive) possible processes for producing that. If this radio feature does not result from intrinsic peculiarities of Geminga, but its proximity and radio-quiet nature (both helping in not hindering the faint diffuse radio emission), other relatively near and energetic radio-quiet pulsars could show similar structures in dedicated interferometric observations.

Key words: pulsars: general – pulsars: individual (J0633+1746, Geminga) – radio continuum: stars – stars: neutron – stars: winds, outflows.

1 INTRODUCTION

Geminga (PSR J0633+1746) is a nearby radio-quiet pulsar discovered as a gamma-ray source and later identified as a neutron star (NS) through optical and X-ray observations (see Bignami & Caraveo 1996 for review). The pulsar period (P ∼ 237 ms) and its derivative (P˙ ∼ 1.1 × 10^{-14} \text{s}^{-1}) correspond to a spin-down age τ ∼ 340 kyr, a spin-down power E_{rot} = 3.3 × 10^{34} \text{erg s}^{-1} and a surface magnetic field B_{surf} ∼ 1.6 × 10^{12} \text{G}. Hubble Space Telescope parallax measurements confirmed the proximity of Geminga (d = 250^{+120}_{-25} \text{pc}) and a proper motion corresponding to a transverse velocity of ∼210 km s^{-1} (Faherty et al. 2007), exceeding the typical sound speed in the interstellar medium (10–30 km s^{-1}). Together with Crab and Vela, Geminga is one of known pulsars with the highest spin-down flux (E_{rot}d^{-2}), allowing detailed studies of weak structures in the immediate vicinity of the NS and its interactions with the local interstellar medium.

Pulsar wind nebulae (PWNe) are common diffuse features surrounding NSs with very different spin-down ages, that result from the interaction of the relativistic pulsar wind and the ambient medium, producing shocks and outflows that can be observed, mostly because of synchrotron and inverse Compton (IC) radiation, in a very broad range from radio to gamma-ray energies (see Kaspi et al. 2006; Gaensler & Slane 2006; Kargaltsev & Pavlov 2008; Pellizzoni et al. 2010).

The complex PWN structures mostly depend on the particular wind outflow geometry and on the ratio of the pulsar speed to the sound speed in the ambient medium (Bucciantini et al. 2005; Romanova et al. 2005; Bogovalov et al. 2005). Well-resolved equatorial “tori” and axial (with respect to the spin axis) “jets” are seen around pulsars moving in the interstellar medium with supersonic velocities (e.g. Crab and Vela pulsars; Weisskopf et al. 2000; Helfand et al. 2001), while in pulsars moving with supersonic speed, as is the case of Geminga, bow-like shapes ahead of the pulsar and tails behind are typically observed (Pellizzoni et al. 2005).

In fact, XMM-Newton observations of Geminga in April 2002 revealed two ∼2′-long tails behind the pulsar, approximately symmetric with respect to the sky projection of the pulsar’s trajectory (Caraveo et al. 2003). Geminga was then observed by Chandra in February 2004 unveiling a new structure ∼25′′-long and ∼5′′-thick, with a surface brightness ∼40 times higher than that of the XMM-Newton tails, starting at the pulsar position and aligned with the proper motion direction (De Luca et al. 2006). A faint arc-like structure was also reported 5–7 arcsec ahead of the pulsar (Pavlov et al. 2004). A deeper Chandra observation carried out in August 2007 confirmed the existence of the axial tail (50′′-long) and of the two outer tails discovered by XMM-Newton (Pavlov et al. 2010), providing an overall X-ray PWN luminosity of L_{0.3–8 \text{keV}} = 3 × 10^{29}d_{250}^{2} \text{erg s}^{-1} (\simeq 10^{-5}d_{250}^{2}E_{rot}). Comparing 2004 and 2007 Chandra observations, Pavlov et al. (2010) found indication that the X-ray tail is composed of variable ∼5′′-long sub-structures (streaming “blobs”). This complex morphology...
was interpreted as synchrotron radiation possibly arising from the shocked pulsar wind collimated by the ram pressure and/or jets emanating along the pulsar’s spin axis.

Apart from diffuse TeV emission around Geminga on larger scales (>2") with respect to the X-ray nebula (Abdo et al. 2009) and a possible detection in the mid-infrared (Damienko et al. 2011), the Geminga PWN has not been detected in other energy bands so far. In particular, since the discovery of Geminga as a gamma-ray source, many observers have attempted to detect it at radio frequencies, both as a continuum and as a pulsating source, providing only tentative detections of weak pulsed emission at low frequencies (~100 MHz; see Kuzmin & Losovsky 1997a,b; Malofeev & Malov 1997; Shitov et al. 1997; Shitov & Pugachev 1998; Vats et al. 1997, 1999). Kassim & Lazio (1999) reported upper limits on the continuum emission (Very Large Array [VLA] data) at 74 MHz (<56 mJy) and 326 MHz (<5 mJy) reconciling their nondetection with previous pulsed detections by invoking intrinsic or extrinsic (refractive interstellar scintillation) variability. At higher frequencies, Spoelstra & Hermsen 1984 reported an upper limit of 0.5 mJy at 21 cm (Westerbork Synthesis Radio Telescope data) and 1 mJy at 6 cm (VLA data). More recently, Giacani et al. 2005 presented a high-resolution (24") study of the H I interstellar gas distribution around Geminga including a 1.4 GHz upper limit of ~0.4 mJy in the pulsar direction. Here we present the results of the deepest VLA interferometric observation of Geminga performed so far.

2 VLA OBSERVATIONS AND DATA ANALYSIS

Geminga was observed at 4.8 GHz (6 cm), with a bandwidth of 50 MHz with the VLA in D configuration (program AP468). The observation was performed on 2004 July 24 for a total of 6.0 on-source hours, with the antennas pointed at R.A.(J2000) = 06\(^\circ\)33\(^\prime\)54\(\alpha\)02, Dec.(J2000) = 17\(^\circ\)46\(\alpha\)11.5. Calibration and imaging were performed with the NRAO Astronomical Image Processing System (AIPS) software package. The flux-density scale was calibrated by observing 0137+331 (3C48). The source 0625+146 was observed at intervals of 30 minutes and used as a phase calibrator. The surface brightness image was produced following the standard procedures: Fourier-Transform, Clean, and Restore implemented in the AIPS task IMAGR. We averaged the 2 IFs together in the gridding process under IMAGR. Self-calibration was applied to remove residual phase variations.

In Fig. 1 we show a ~8’-side field of the radio continuum emission around Geminga. The image has a FWHM beam of 15\(\prime\)2 x 11.5 (position angle, \(P_A = 46.5^\circ\)) and a noise level of 25 \(\mu\)Jy beam\(^{-1}\) (1\(\sigma\)). A radio feature, with a peak of brightness at >10\(\sigma\) significance level, located at R.A.(J2000) = 06\(^\circ\)33\(\alpha\)33\(\mu\)4.22 (±0.04), Dec.(J2000) = 17\(^\circ\)46\(\alpha\)11.22 (±0.42) (through AIPS task JMFIT), has been detected. The absolute astrometric accuracy of VLA observations is linked to the uncertainty in the phase calibrator position, which is better than 0.15 in our case. However, the VLA accuracy can be limited by a number of effects, such as the atmospheric phase stability. For this reason, we adopted for the positioning uncertainty a more conservative figure of 1.5\(\alpha\), which was estimated as the synthesised beam size divided by the signal to noise ratio (see, e.g., Hagiwara et al. 2001).

Figure 1. Geminga field (~8' x 8') at 4.8 GHz resulting from the 6-hours VLA observation performed in D configuration. The beam FWHM is 15.2' x 11.5' and the image sensitivity is 25 \(\mu\)Jy beam\(^{-1}\) (1\(\sigma\)). A zoom of the image, restored with a circular beam of 15.3' x 15.3', is inset in order to evidenciate the slightly elongated nature of the radio feature. The faintest drawn radio contour level corresponds to 75 \(\mu\)Jy beam\(^{-1}\) and the other levels are spaced by a factor of \(\sqrt{2}\).

The observed brightness distribution is more extended than that expected for a point source: it is slightly elongated and fits with a single 2-dimensional Gaussian model with a FWHM major axis of 18.6' ± 1.6', a minor axis of 11.1' ± 0.0', and \(P_A = (64.3\pm6.6)^\circ\), incompatible with beam parameters (the fit with the point-spread function yields a poor reduced \(\chi^2\) of ~2.5 for 5 degrees of freedom). The deconvolved size along the major axis (approximately the direction of Geminga proper motion) is 11' ± 3', while it is unresolved in the transverse direction. The flux density of the source at 4.8 GHz is (0.37 ± 0.05) mJy being calculated by integrating the total intensity surface brightness down to the noise level. No evidence of source variability was found down to ~1.5–2 hours, which is the minimum time-scale that can be probed in our data. At the distance of Geminga, the corresponding radio power is \(S_{4.8\,\text{GHz}} \approx 2.7 \times 10^{38}\,\text{W\,Hz}^{-1}\).

To investigate the presence of such source in our VLA observations, we analyzed an archival dataset at 1.5 GHz in B configuration (program AK147). In this case we obtained an image with a FWHM beam of 40' x 39.98 and noise level of 22 \(\mu\)Jy beam\(^{-1}\) (1\(\sigma\)). We did not found any source in correspondence to the 4.8 GHz detection. Giacani et al. 2005 reported on a study of the H I (21-cm line) interstellar gas distribution on a 40' x 40' field around Geminga based on VLA and Effelsberg radio telescope data. Based on the line-free channels of the 1.4 GHz cube, they produced a radio continuum image with 24' angular resolution, confirming the

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3 See http://www.aips.nrao.edu/
4 For more details, see the VLA observation status summary at http://www.vla.nrao.edu/astro/guides/vlas/current/
5 We checked our capability to distinguish point-like from slightly elongated sources, such as the detected feature, by performing detailed simulations in which we artificially injected point sources in the raw VLA data.
nondetection of any source at this frequency, either point-like or extended, down to a noise level of 0.14 mJy beam$^{-1}$ (1σ).

Hence, the presently available data do not allow one to constrain the thermal or non-thermal nature of the emission, but, if the radio source is steady, we can set an upper limit on the spectral index $\alpha_{1.4 \text{ GHz}} < 0.1$ (this value has been calculated by considering that at 1.4 GHz the total flux density is below $3\sigma_{1.4 \text{ GHz}} = 0.42$ mJy). We note however that if the radio source is variable, this limit is unreliable, since the reported observations are not simultaneous.

We computed the coordinates of the Geminga pulsar at the epoch of the reported VLA observation by projecting the accurate optical absolute position by Caraveo et al. (1998) using the proper motion measurement by Faherty et al. (2007): RA = 06h33m54.24s, Dec. = +17°46′13.9′′ with errors $<0.1′$. The pulsar is within the reported diffuse feature, marginally displaced by 2.7 ± 1.8 arcsec from the radio peak emission and in association with a radio brightness of 0.26 mJy beam$^{-1}$ (∼80% of the peak flux; Fig. 2). The probability of random association between the radio feature and the Geminga PWN region (approximately FWHM beam size divided by the field of view) is $<10^{-3}$. We examined radio, optical and near-infrared catalogs looking for possible background objects of different nature (e.g. an AGN jet), but no counterpart compatible with the observed structure was found.

In order to compare the radio and X-ray morphologies of the structures associated to Geminga, we retrieved a public Chandra ACIS-S imaging exposure of the field performed close to the VLA observation (Obs. ID 4674; De Luca et al. 2006; Pavlov et al. 2006). The ∼20-ks-long observation was carried out on 2004 February 07 (168 days before the VLA observation) in ‘Timed Exposure’ mode using a 1/8 subarray. Geminga was positioned in the back-illuminated ACIS-S3 chip, sensitive to photons between 0.2 and 10 keV. The data were processed using the Chandra Interactive Analysis of Observation software (CIAO, version 4.2) and we employed the CALDB 4.3 calibration files. Standard screening criteria were applied to generate a 0.5–8 keV image of the field of Geminga. Using the Chandra aspect tool we found a small offset in the astrometry ($\Delta$RA = 0′01, $\Delta$Dec. = 0′0′′). After fixing the offset, in order to assess the absolute astrometry of the Chandra data set, we computed the position of Geminga with the WAVDETECT task. We localized it at ∼0′0′3 from the position expected on the basis of the source absolute optical position and proper motion, well within the typical ACIS-S localization accuracy. The X-ray contours obtained from the 2004 Chandra observation and related to the pulsar and to the axial PWN tail (see also De Luca et al. 2006; Pavlov et al. 2006) are shown in Fig. 2. The deconvolved length of the radio feature (∼10′′) is smaller than the whole time-integrated (2004 and 2007 Chandra combined data) X-ray tail, but larger than the substructures (typically ∼5′′-long ‘blobs’) detected by Chandra in individual observations (Pavlov et al. 2010).

### 3 DISCUSSION

A VLA observation at 4.8 GHz unveiled a ∼10′′-long radio feature with flux of ∼0.4 mJy associated with the Geminga pulsar and its PWN. Significant contamination from Geminga persistent pulsed radio emission is very unlikely: given the tight upper limits on pulsed flux density at low frequency (e.g. < 0.05 mJy at 0.4 GHz; Burderi et al. 1999), the contribution of pulsed emission to the total observed flux at 4.8 GHz would be <0.1% for the mean spectral index of radio pulsars ($\langle \alpha \rangle = 1.8 \pm 0.2$; Maron et al. 2000) and could at most reach ∼15% even in the extreme case of a flat spectrum. The occurrence of transient pulsed (or continuum) radio emission in isolated NSs in not unheard-of, but it involves at our present knowledge pulsar classes showing a totally different phenomenology from that of the Geminga pulsar, like magnetars and rotating radio transients (Rea & Esposito 2011; McLaughlin et al. 2011). Furthermore, the emission models mentioned above, as well as any other kinds of magnetospheric emission originating very close to the NS surface (and hence appearing as point-like at the spatial resolution of the available observations), are disfavored by the evidence for a slightly elongated feature, together with the occurrence of a marginal offset between the NS position and the radio emission centroid (∼2′′7).

The latter two features and the tendency of the radio emission to distribute along the direction of the axial X-ray tail, naturally lead to an association with the Geminga PWN. Pavlov et al. 2010 and references therein observed that the axial tail may result from the shocked pulsar wind collimated by the ram pressure (i.e. a bow-shock) or from a jet emanating along the pulsar’s spin axis and perhaps aligned with the direction of motion. In the frame of the standard bow-shock models, radio PWNe are generally interpreted as arising from cooling of X-ray-emitting leptons (Kennel & Coroniti 1984). The smaller size of the radio nebula of Geminga (with respect to the whole, time-integrated, ∼50′′ long X-ray tail) apparently contradicts this hypothesis, unless we associate the observed radio feature to the variable streaming ‘blobs’ of ∼5′′ diameter, possibly constituting the X-ray axial tail as observed in 2004 (Pavlov et al. 2010). Furthermore, synchrotron models explaining the X-ray tails as pulsar wind shocked by the ram pressure

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6 $S(\nu) \propto \nu^{-\alpha}$, where $\alpha$ is the spectral index.
7 See http://asc.harvard.edu/ciao/threads/index.html.
8 See http://cxc.harvard.edu/cal/ASPECT/fix_offset/fix_offset.cgi.
9 See http://cxc.harvard.edu/cal/ASPECT/celmon.
due to the NS’s supersonic motion typically require relatively low magnetic fields (∼10–100 μG; Caraveo et al. 2003, Pavlov et al. 2006). With such low magnetic fields, the radio emission arising from the cooling of the X-ray emitting electrons, would be placed well outside the VLA field of view due to the large proper motion of Geminga: e.g. more than 0.5 deg off the position of the X-ray emission for a magnetic field of 100 μG (Caraveo et al. 2003). In summary, ram-pressure collimated PWN models can be applied to our case only if additional processes, such as adiabatic expansion from hypothetical over-pressurized substructures of the tail (not observable at the present stage) provide a cooling power much higher than the synchrotron one and/or if radio emitting electrons are directly accelerated at the PWN shock, i.e. they are not originated from the cooling of high-energy electrons as in standard PWN models. In this respect, we note that the radio “wisps” observed in the Crab PWN are produced by the same process as the higher-energy ones, although the mechanism by which this particle spectrum is generated is still not known (see e.g. Bietenholz 2006).

Alternatively, the radio tail of Geminga could in principle be ascribed to a (magnetically-collimated) jet, in which the radio emission could directly result from radio-emitting electrons freshly-injected along the spin-axis at the jet formation site, or from internal shocks in which the accelerated X-ray-emitting leptons cool down to radio energies on the observed short space and time scales (see e.g. Benford 1984; Komissarov & Lyubarsky 2004; Meier 2003 for possible models of magneto-hydrodynamic jet produced by isolated pulsars).

In the latter case, magnetic fields ≥0.05 G are required in order to avoid the occurrence of an additional (i.e other than synchrotron) cooling process. As already noticed for the case of the ram-pressure collimated PWN models, there is no evidence of such high fields in other PWNes. However, in the first place, large magnetic fields due to the NS dipole are in principle available at the pulsar light cylinder (Blc ∼ 10^3 G for Geminga) and in its surroundings. In the second place, an observational bias may also be at work here. In fact, despite the growing number of jet-like structures around NSs resolved in X-rays (Kargaltsev & Pavlov 2008), no ‘genuine’ magneto-hydrodynamic radio jet around pulsar was detected so far (see e.g. Cohen et al. 1983 for VLA mapping of numerous pulsar fields), possibly excepting PSR J2021+4026, another radio-quiet gamma-ray pulsar, located at the edge of the supernova remnant G 78.2+2.1 (Trepl et al. 2010). Thus, it cannot be excluded that pulsar radio jets might be observable only in nearby and radio-quiet pulsars, not hindering their close environment by bright magnetospheric radio emission and having magnetic fields much stronger than those related to other PWN structures placed at larger distances from the NS surface. Interestingly enough, this hypothesis may be checked by a series of deep radio interferometric exposures. Scaling our result for Geminga, this survey could unveil jet-like structures in few other near (<1 kpc) and energetic (Etot ≥ 10^{43} erg s^{-1}) radio-quiet pulsars, some of them recently discovered by the Fermi satellite (Abdo et al. 2009).

Finally, we note that a further possible explanation of the Geminga radio tail is the leakage of radio-emitting electrons (with Lorentz factor γ ∼ 10–100) directly from the open field lines of the magnetosphere. The maximum current through the magnetospheric accelerator (i.e., the Goldreich-Julian current; see e.g. Wang et al. 1998 and references therein) and then the maximum particle flux escaping from Geminga open field lines can be estimated from N ∼ Ω^2 B^2_{surf} R^4/2ec ∼ 5 × 10^{35} s^{-1} (where Ω is the pulsar angular velocity, and the NS’s radius R is assumed to be 10 km).

The expected synchrotron power at 4.8 GHz, for a random distribution of pitch angles, can be roughly obtained from:

\[ W_{\text{radio}}^{\text{synch}} \approx \frac{4}{3} \sigma_T \gamma^2 U_B c N_e \tau_{\text{synch}} \sim 10^{35} \gamma \epsilon \text{ erg s}^{-1} \]

where \( \tau_{\text{synch}} \equiv m_e c/(\epsilon \gamma U_B) \) is the synchrotron cooling time of the electrons, \( U_B \equiv B^2/(8\pi) \) is the magnetic field energy density and \( \epsilon \) is the fraction (w.r.t. \( N \)) of radio emitting particles. The observed luminosity of \( 10^{39} \text{ erg s}^{-1} \) at 4.8 GHz would then be matched for \( \gamma \epsilon \sim 10 \), implying a magnetic field of \( B \sim 20 \text{e}^2 \text{ G} \) in the area of the emission. If this magnetic field is associated to the NS dipole, the emitting region would then be placed at a distance of \( D_{\text{em}} \sim 5 \times 10^9 \text{e}^{-2/3} \text{ cm} \) from the NS surface. In summary, for \( \epsilon \sim 0.5 \) (in turn implying \( D_{\text{em}} \) of the order of ten light cylinder radii, \( \gamma \sim 20 \), \( B \sim 5 \text{ G} \), and \( \tau_{\text{synch}} \sim 0.05 \text{ yrs} \)), this model would provide a cooling and possibly expanding diffuse radio feature protruding from the Geminga pulsar. If this model is correct, two geometrical constraints should be simultaneously satisfied by the Geminga pulsar: the radio pulsar beam not intersecting the line of sight and the leaking electrons producing a relatively narrow cone of radio emission roughly aligned with the projection of the pulsar proper motion. This would suggest that Geminga is a nearly aligned rotator, with the spin axis almost aligned with the proper motion and with the velocity vector close to the plane of the sky.

### 4 CONCLUSIONS

We have reported on the discovery of a radio emitting structure with a flux of ∼0.4 mJy at 4.8 GHz, associated with the Geminga pulsar and roughly aligned with the direction of the neutron star proper motion. The source appears slightly extended (∼10′′-long) but further deeper observations are needed to confirm the elongation unambiguously. The nature of this emission is unconstrained by present data, but a combination of dedicated radio interferometric and X-ray observations is expected to shed light on the underlying physical process and likely unveil similar radio tails in other radio-quiet pulsars.

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11 See also e.g. Wang et al. 2001 and Gaensler et al. 2003 for examples of parameters of typical bow-shock PWNe simultaneously detected both in X-rays and radio.

12 In particular, bulk flow velocity measurements in the radio band could assess the indication of motion/variability of X-ray blobs along the axial tail, suggestive of a jet-like interpretation, obtained by comparing Chandra observations at different epochs (Pavlov et al. 2014).
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