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Upper limits on the pulsed radio emission from the Geminga pulsar at 35 & 327 MHz

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Abstract. We report here our observations at 35 MHz and 327 MHz made in the direction of the γ–Ray pulsar Geminga. Based on the observed absence of any significant pulsed emission from this source above our detection thresholds at the two frequencies, we obtain useful upper-limits for the average flux to be 75–100 mJy at 35 MHz, and 0.2–0.3 mJy at 327 MHz. We discuss a few possible reasons for the "radio-quiet" nature of this pulsar at frequencies other than around 100 MHz.

Key words: pulsars: individual: J0633+1746

1. Introduction

Geminga, as known today, the γ–ray source in the Gemini constellation, was first observed by NASA's SAS–2 γ–ray astronomy mission (Fichtel et al. 1975). An enhancement of a little more than a hundred photons, in the anticentre region was detected and was thought to be from an extended nebula, since the initial attempts to associate it with any known source were unsuccessful. Noting the absence of any radio pulsar close to $\gamma 195+5$ (as the source was then called), the papers announcing the discovery (Kniffen et al. 1975; Fichtel et al. 1975) made an explicit mention of the IC443 SNR close to the source.

The first systematic radio observations in the direction of the γ-ray source, carried out by Bignami et al. (1977) at 610 MHz, did not result in a detection. With the shrinking error bars on the position of the γ-ray source, it soon became clear that the source is more like a point source (Masnou et al. 1981), and this led to several attempts to search for radio emission, in particular, to search for a radio pulsar (Mandolesi et al. 1978; Mayer-Hasserlwander et al. 1979; Seiradakis 1981; Manchester & Taylor 1981), but these attempts were unsuccessful. In the two years that followed, strong evidence was accumulated to identify the X-ray source 1E0630+178 as the counterpart of Geminga (Bignami et al. 1983, and references therein), and an optical counterpart was also detected (Bignami et al. 1988; Halpern & Tytler 1988, and references therein).

The first evidence for the Geminga source being a pulsar came from a ROSAT observation (Halpern & Holt 1992). A clear periodicity of about 237 milliseconds was detected, and was subsequently verified by EGRET (Bertsch et al. 1992). With the added advantage of the knowledge of an accurate period and its time derivative (derived from the high energy observations), a series of radio observations were made hoping to detect the periodicity, but with no success. The apparent 'radio-quiet' nature of the Geminga pulsar led to the suggestion that the radio emission beam is probably not directed towards the Earth. Alternative suggestions were also put forward, for example, that the absense of radio pulses from Geminga may be due to a genuine lack of radio emission (Halpern & Ruderman 1993).

After this series of unsuccessful attempts the radio investigations had virtually ceased during the past few years, until the reported detections of radio pulses from Geminga at 102 MHz at the Pushchino Radio Observatory (Kuzmin & Losovsky 1997; Malofeev & Malov 1997; Shitov & Pugachev 1997). All the three groups reported the detection of the radio signal at roughly the same dispersion measure, but different flux densities and pulse widths. While Kuzmin & Losovsky reported an average flux of about 100 mJy, Malofeev & Malov, and Shitov & Pugachev found average fluxes of 60 ± 95 mJy and 8 ± 3 mJy, respectively. From their observations in December 1996 and January 1997, Malofeev & Malov (1997) concluded that the observed intensity was highly variable.

In this paper, we report the results of our observations targeted to detect the Geminga pulsar at 35 and 327 MHz using the Gauribidanur Telescope and the Ooty Radio Telescope respectively. In the following Sect. 2, we describe our observational set up at the two telescopes, the analysis procedures used and the results from these observations. At the end, in Sect. 3, we discuss the possible reasons for the apparent lack of detectable radio emission from this pulsar at frequencies other than around 100 MHz.

2. Observations, analysis and results

2.1. *The 35 MHz observations using the Gauribidanur telescope*

These low-radio-frequency observations were made using the Gauribidanur Telescope located at a latitude of $13^\circ.6$ N in south India. The East-West arm of the dipole T-array, with an effective

Send offprint requests to: R. Ramachandran collecting area of about 16,000 m^2, was used with its limited tracking facility (Deshpande et al. 1989). In the receiver set-up used (Deshpande et al. 1998), a 1-MHz band centred at 34.5 MHz was down-converted to a 10-MHz IF band, which was sampled using harmonic sampling with a clock rate of 2.1 MHz. The signal voltages were digitized to two-bit 4-level samples and directly recorded using a PC-based data acquisition system. The recorded data were later processed off-line on a general-purpose computer.

In the off-line processing, the data were Fourier transformed in suitable blocks of the 2-bit samples to obtain an equivalent spectrometer output for a chosen number of narrow channels spanning the 1.05 MHz band, so as to allow for suitable dedispersion. At 35 MHz, for a DM of $\sim$3 pc cm^{-3}, the dispersion delay across the band is about half a second, requiring sufficiently narrow channel widths. For the Geminga data, the number of such channels was 256 (each about 4 kHz wide). In each channel, the power output was integrated in time for about 2 milliseconds. The series of such spectra in each observation were examined for possible interference and where found, the corresponding time and frequencies were noted for data rejection during futher processing steps. The interference-free data were then folded to obtain an average profile (for each channel) over the apparent rotation period of the pulsar (or over stretches that are integral multiples of the period).

Such average profiles for the 256 spectral channels from a given data set were combined after dedispersing for a range of assumed values of the dispersion measure. The combined profiles, one for each of the DM values, were tested for existence of a significant ‘pulse’ feature. The DM range of 0-60 pc cm^{-3} was covered with finely spaced steps. The data sets subjected to the above mentioned DM search test were of three types, where the average profiles in each of the 256 channels were obtained with a folding interval equal to (i) the pulsar period, (ii) twice the period and (iii) ten times the period. The case (i) gives the so called average profile, which is tested for a single pulse-feature with a significant contrast referenced to the ‘off-pulse’ baseline. The data in the case (ii) was tested for two similar ‘pulse’ features with a separation equal to the pulsar period. In low-radio-frequency observations (like ours) where the interference could be severe, tests like (ii) are quite effective in distinguishing between the real pulsar signal and possible artefacts due to interference or random noise. In these two cases, the profiles smoothed to a variety of coarser resolutions (allowing optimum detection for a range of pulse-widths) were also tested for ‘pulse’ features. The 10-period average profile (case iii) in each trial, was Fourier transformed and the spectrum was examined for a significant feature corresponding to the rotation frequency of the pulsar.

A total of seven sets available from our observations during March-July 1997 were analysed and tested as described above. The results of the above mentioned tests were also examined for only parts of the band in some cases, to assess if the main contribution came from only a few spectral channels. Tests were also conducted on sets obtained by combining two or more of the available original sets/subsets. Before combining, the cross correlation between the sets, i.e. the 2-dimensional intensity maps (intensity as a function of the pulse phase and frequency), was performed to find the relative phase shift corresponding to the maximum correlation. The two input sets were summed after compensating for the relative shift. For further combinations, the above procedure was repeated. The advantage in such a procedure is that it looks for the best match between the possible patterns in the two component sets due to dispersion delay gradients, if any, but without committing the process to any particular dispersion measure. Thus, the flexibility for a DM value search is not sacrificed during the combining procedure.

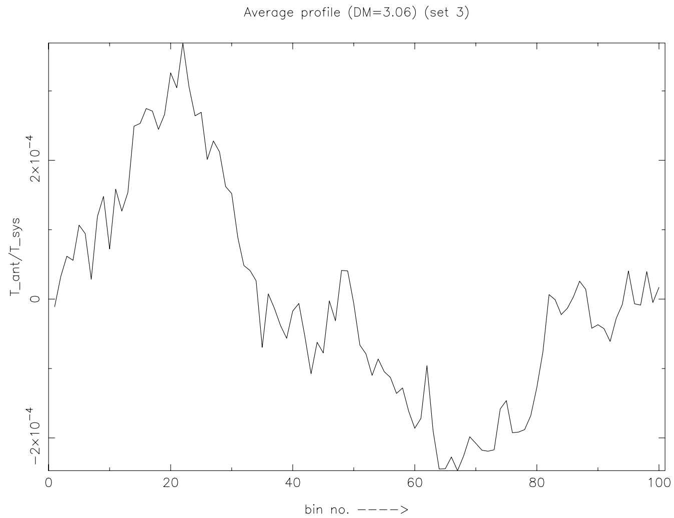

Fig. 1. Integrated profile (across one period) corresponding to set No.3 at 35 MHz, after 20-bin smoothing.

Out of all our observations, what we consider as the ‘best-case’ results came from data sets No. 3 and 7. The set No.3, with $\sim$600 seconds of observation, was the lone set that showed a somewhat significant feature at 4.22 Hz in the power spectrum of the average profile over 10-periods (case iii). The feature was most prominent for DM $\sim$3 pc cm^{-3}. Also, the corresponding average profile over a two-period stretch *did* show two features separated by one pulse period. However, it also showed a comparable additional bump next to only one of the features in this two period stretch. We show in Fig. 1 the corresponding average profile over one-period stretch. The *mean* has been subtracted from the profile, which has been smoothed by a 20-bin window. The expected noise is 1.2×10^{-4} ($1\ \sigma$) in the same units as on the Y-axis. Although, this is one of the ‘best-case’ profiles we have (particularly as the observation was not affected by any noticeable interference), we consider this profile consistent with what may simply be system noise.

Another set of our observations, set No. 7, showed some interesting results. It had four times more integration than set No.3, but we had to reject many (about 20%) frequency channels which were affected by interference. Over the range of DMs examined, the power spectrum analysis of this data set *did not* show any significant feature at 4.22 Hz, nor did it have two similar looking pulse-like features when the time series was folded at twice the rotation period of the pulsar. However, when

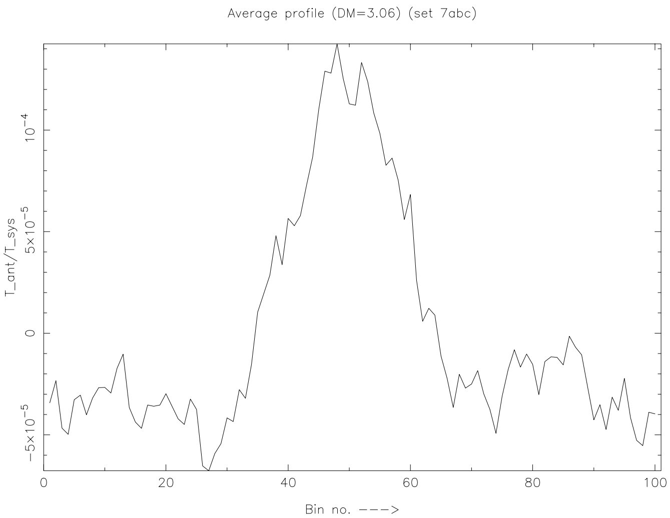

Fig. 2. Integrated profile (across one period) corresponding to set No.7 at 35 MHz, after 20-bin smoothing.

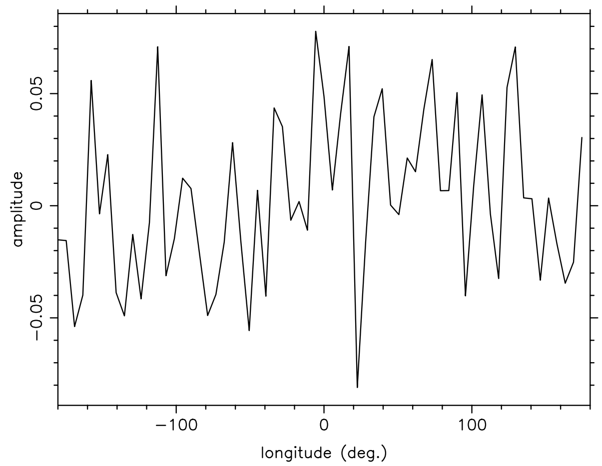

Fig. 3. Integrated profile over one-period stretch at 327 MHz.

the data were folded at the pulse period, and dedispersed (for a DM ∼3 pc cm^{-3}), the average profile showed a significant looking pulse feature, Fig. 2. The noise level in this profile is about 6×10^{-5} (1 σ), and we have used this profile to derive a useful upper limit (3-σ) of about 75 to 100 mJy for the average flux at 35 MHz. We conclude that this profile is also entirely due to noise. In fact, we wish to emphasize these as instructive examples of how noise can produce very *appealing profiles*! It is worth mentioning that similar situations occured at some other values of DM too, signalling no significant preference for a DM close to 3 pc cm^{-3}.

2.2. The 327 MHz observations using the Ooty telescope

Observations at 327 MHz were conducted on 22$^{\rm nd}$ November 1995 using the Ooty Radio Telescope (ORT), India (Swarup et al. 1971). The telescope, an offset-parabolic cylindrical dish, has an effective collecting area of about 8000 m^2, which corresponds to ∼3 K/Jy. With the improved feed system (Selvanayagam et al. 1993) the system temperature is typically about 200 K ($T_{\rm rec} + T_{\rm sky}$). The telescope operates at a fixed centre frequency of 327 MHz (with about 10 MHz bandwidth). As the dipoles in the feed array are oriented North-South, the telescope is not sensitive to the other (East-West) component of polarisation.

The front-end electronics down-converts the signal to an intermediate frequency (IF) of 30 MHz. This IF-signal is used as an input to a special-purpose pulsar processor (see McConnell et al. 1996 for details), which uses four filters with width 2.5 MHz each, spanning the band from 25 to 35 MHz. The signals from each of the filters are sampled using harmonic complex sampling at the Nyquist rate. Each of these digital sample trains is Fourier transformed to obtain 256 spectral channels across each of the 2.5 MHz bands. Thus, each of the 1024 channels produced has a width of ∼10 kHz. The total-power outputs from the channels are combined on-line after dedispersion (for an assumed DM value) to produce a single time series with samples at intervals of $102.4\ \mu{\rm sec}$. These time series were averaged synchronously with the apparent pulse period over blocks of every 2^{20} samples separately to obtain an average profile across 64 bins spanning the predicted (apparent) period of the Geminga pulsar. The mean total-power in each of these blocks was computed and subtracted from the average profile for that block. The subtracted means of all the blocks were stored separately and used as measures of the system temperature during flux calibration.

In the present case, a DM of 2 pc cm^{-3} was used for the on-line dedispersion. Although, the *true* DM may be somewhat different from this value, the possible smearing due to the difference is unlikely to be serious becasue, (a) a DM of 1 pc cm^{-3} corresponds to a differential delay of only ∼2 ms across the band of 10 MHz at 327 MHz; (b) the distance to Geminga is about 100 pc; and (c) the pulse duty cycle is expected to be 10-20%.

Fig. 3 shows the average profile based on 6 Hrs of integration during our 327 MHz observation towards the Geminga pulsar. As can be seen, there is no pulsed signal above our detection limit. If we assume that the duty cycle of the radio counterpart of Geminga is the same as that observed in γ–rays ($\sim$ 20%), then our 327 MHz observation implies an upper limit of 0.2–0.3 mJy for the average flux (corresponding to a 3σ level). To the best of our knowledge, this represents by far the most stringent limit available in the frequency range 300-400 MHz.

The uncertainty in the quoted limits is mainly due to the corresponding uncertainty in the flux calibration. At both the frequencies, the telescope gains were calibrated using observations on continuum sources.

3. Discussions

We have reported here the results of our observations aimed at searching for the radio counterpart of the Geminga pulsar at 327 MHz and 35 MHz. At both these frequencies, we did not find any significant pulsed emission allowing us to estimate useful upper limits, of 75–100 mJy at 35 MHz and 0.2–0.3 mJy at 327 MHz, for the average pulsed emission at the two well separated frequencies. In the light of these and many other earlier attempts, the reported detection of this pulsar at 102 MHz by Malofeev & Malov (1997) appears puzzling. However, as they themselves report, the strongest support for their positive detection of the pulsar at 102 MHz comes from the fact that the pulses on each observing session arrived at the expected phase pre-calculated on the basis of the available ephemeris.

They also observed that the pulsing flux at 102 MHz is highly variable ($S_{102} = 60 \pm 95$ mJy). With the mean value of 60 mJy and with a spectral index of ~ -2, we would expect to receive an average flux of more than about 6 mJy from this pulsar at 327 MHz. However, as mentioned above, we do not see any significant emission above a 0.2 mJy level. This would imply a spectral index for the pulsed emission to be < -4.5, giving this pulsar the steepest spectrum in this frequency range. The observed intensities of nearby pulsars, like J0437–4715, are known to fluctuate by a factor of a few due to interstellar diffractive scintillation, with time scales of the order of an hour or so. We observed Geminga at 327 MHz for about 6 hours, and we consider it unlikely that the pulsar would have stayed at a 'low-state' due to scintillations during most of that observation.

From the properties of about 800 known pulsars, we expect the pulsed emission from a pulsar to be detectable over a reasonably wide range of radio frequencies. However, given the claimed detection at 102 MHz, and our failures at 35 and 327 MHz, we are left to speculate on the possibilities of having very weak or no emission at frequencies other than around 102 MHz. One possibility, where the 102 and 327 MHz results would appear consistent is that the trajectory of our line-of-sight is at the edge of the emission cone at 102 MHz. Then, at higher frequencies, the line-of-sight is more likely to miss the emission cone, if it becomes smaller with increasing frequency. This should not be too surprising, as we have at least one known example, PSR B0943+10, where this is almost certainly the case. The observed flux from this pulsar drops down quite rapidly at frequencies above roughly 600 MHz (Malofeev & Malov 1980; Lorimer et al. 1995) while on the other hand, it does not show a spectral turn-over down to 35 MHz (Deshpande & Radhakrishnan 1992; 1994). The non-detection of the Geminga pulsar at 35 MHz can also be understood in such a case, if the spectrum has a turnover in the range 35-100 MHz. From observations of other pulsars, we know that such spectral turn-overs at about 60-100 MHz are not unusual (see Deshpande & Radhakrishnan 1992, for example).

The other possibility is that the reported value of the average flux at 102 MHz (Malofeev & Malov 1997; Kuzmin & Losovsky 1997) is an over-estimate and the value is below or about 10 mJy, consistent with that found by Shitov & Pugachev (1997). In such a case, a straight spectrum from 35 to 300 MHz, implying a spectral index of about –2.5, would be consistent with our limits.

To conclude, the main points are summarised below.

- We have searched for pulsed radio emission from Geminga at 35 and 327 MHz, using a variety of stringent detection criteria.
- At both the frequencies, we *did not detect* any significant emission from the source, implying upper limits for the average flux; namely, 75–100 mJy at 35 MHz, and 0.2–0.3 mJy at 327 MHz.
- We suggest that the lack of emission from the pulsar at frequencies other than around 102 MHz may be understood in terms of a peculiar geometrical situation or in terms of a large error in the estimated average strength at 102 MHz.

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