Letter to the Editor

Hipparcos positioning of Geminga: how and why[*],[**]

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Abstract. Accuracy in the absolute position in the sky is one of the limiting factors for pulsar timing, and timing parameters have a direct impact on the understanding of the physics of Isolated Neutron Stars (INS). We report here on a high-accuracy measurement of the optical position of Geminga ($m_v = 25.5$), the only known radio-quiet INS. The procedure combines the Hipparcos and Tycho catalogues, ground-based astrometric data, and Hubble Space Telescope (HST) Wide Field Planetary Camera (WFPC2) images, to yield Geminga's absolute position to within $\sim 40\ mas$ (per coordinate). Such a positional accuracy, unprecedented for the *optical* position of a pulsar or an object this faint, is needed to combine in phase γ-ray photons collected over more than 20 years, i.e. over 2.5 billions of star' revolutions. Although quite a difficult task, this is the only way to improve our knowledge of the timing parameters of this radio silent INS.

Key words: space astrometry; pulsar; Geminga

1. Introduction

Geminga is the only known example of a bona fide pulsar that cannot rely on well established radio timing techniques. The radio silence of the source implies the impossibility to measure its position and distance as inferred from the optimization of the radio timing parameters and from the dispersion measure of the radio pulses. To measure position, distance and timing

parameters of Geminga, all other branches of astronomy had to be exploited in a 20 y long chase, recently summarized in Bignami and Caraveo (1996 and references therein). Briefly stated, the source was discovered in high energy γ-rays by the SAS-2 satellite in 1972, and studied in more detail by the COS-B mission. An X-ray counterpart has been proposed in 1983 and an optical one, refining the position, in 1987/88. However the breakthrough came with the discovery of the 237 msec periodicity in the ROSAT data. Finding the same periodicity in the contemporary data of EGRET, as well as in old archival COS-B and SAS-2 data, yielded the value of the period derivative and thus of the object's energetics. The discovery of the proper motion of the optical counterpart confirmed the optical identification and provided the absolute position of Geminga to within 1". Next came the measure of the source parallactic displacement, yielding a precise measure of its distance. Our knowledge of the Geminga pulsar is now good enough to warrant, "honoris causa", inclusion in the radio pulsar catalogue Taylor, Manchester and Lyne (1993). In it, the radio silent Geminga stands out for the remarkable accuracy achieved in the measure of its parameters. For example, the period derivative of Geminga is known with an accuracy greater than that of the Crab. Such an accuracy is mainly due to the very stable behaviour of this $310^5 y$ old neutron star, which does not seem to be affected by glitches. Indeed, Mattox, Halpern and Caraveo (1996) claim that, during the first 3 years of coverage with EGRET, every pulsar revolution can be accounted for. This means that the γ-ray photons, collected in week-long observing periods taken several month apart over a span of years, can be aligned in phase to form the well-defined, spiky light curve seen in high energy γ-rays. Had Geminga been a glitching pulsar, like Vela or Crab, it would have been impossible to obtain a satisfactory (and accurate) long-term solution.

Moreover, the growing high energy coverage offers the possibility to refine the knowledge of this source's timing parameters, including the second period derivative and, thus, the neutron star braking index. However, to take full advantage of the potential offered by γ-ray astronomy, very accurate values of the absolute source coordinates are required to determine the barycentric arrival time of each photon. Any error in the source coordinates affects the accuracy of the corrected arrival times and thus hampers the global accuracy of the procedure. Mattox, Halpern and Caraveo (1996) have shown that the uncertainty in the source absolute positioning can induce an error in the barycentric correction up to 2.3 δ_e msec, where δ_e is the source positional uncertainty (in arcsec) projected on the plane of the ecliptic. Thus, with a sensitivity to phase errors of $< 10^{-2}$ over a period of 237 msec, the presently available positional accuracy of ~ 1" is the limiting factor for Geminga's photon timing analysis. As mentioned before, high-energy γ-ray photons have been collected unevenly over the years: during 1972-1973 by the SAS-2 satellite, during 1975-1982 by the COS-B mission and again from 1991 by the Compton Gamma-Ray Observatory. To lock in phase > 20 years of γ-ray data an improvement in positional accuracy of at least one order of magnitude is required. To achieve this challenging goal we have exploited the angular resolution of HST in conjunction with the accuracy of the Hipparcos reference frame (ESA, 1997).

2. From Hipparcos to HST

However, to tie Geminga into the Hipparcos system, one has to overcome the 16-18 magnitude gap between the bright stars used as a primary reference and our $m_v = 25.5$ target, an impossible dynamical range for a single instrument. Moreover, one has to link astrometric images covering a field of view of $\sim$1 square degree to those obtained by the WFPC2 of HST, 14,000 times smaller in area.

The principle of our method, described in detail by Caraveo et al. (1997), is to cover the field of interest with images of increasingly smaller field of view and deeper limiting magnitude. The transfer of the reference system from one step to the next is based on sets of stars of intermediate magnitude. A similar procedure has been successfully applied (e.g., Chiumiento et al, 1991; and Zacharias et al, 1995) for the determination of absolute positions of optical counterparts of extragalactic radio-sources. However, these cases were less critical, as the differences in magnitude were only 8-10 and two or three intermediate steps were usually sufficient to bridge the gap between the reference stars and the targets. We note that the FK4 coordinates of the 16 mag Crab pulsar were obtained by MacNamara (1971) with a two step procedure.

In the case of the 9 magnitude fainter Geminga, we had to use a new five-step procedure starting with astrometric plates taken at the Osservatorio Astronomico Torino (OATo), and ending with images taken with the Planetary Camera 2 on HST (see Fig. 1 for a comparison of the two images). The observational material actually used in this work is listed in Table1. To calibrate the astrometric plates we have used the best op-

tical reference frame in the sky which is now provided by the Hipparcos and Tycho Catalogues. These catalogues have been constructed in such a way that the Hipparcos reference frame coincides, to within limits set by observational uncertainties, with the International Celestial Reference System (ICRS). The latter system is defined by the adopted positions of several hundred extragalactic radio sources. It supersedes, although it is consistent with, the optical reference frame defined by the FK5 catalogue, which was formally based on the mean equator and dynamical equinox of J2000. While the Hipparcos Catalogue lists 118,000 stars as faint as $m_v = 12.4$ whose positions and annual proper motions are known to typically 1 mas at epoch J1991.25, the Tycho Catalogue contains more than one million objects, the astrometric parameters of which have been measured with a median precision of 25 mas. With about 3 stars per square degree the Hipparcos Catalogue, although of vastly superior precision, is not suitable for our purpose, which can be better fulfilled by the relatively less accurate but denser Tycho Catalogue. However, since the proper motions listed in the Tycho Catalogue are accurate only to approximately 25 mas/yr, we have propagated the Tycho positions (epoch J1991.25) to the OATo 38 cm refractor plate epoch (J1984.19) using the proper motions provided by the PPM catalogue (Röser and Bastian, 1993). This is an all-sky list of 378,910 stars referred to the FK5 system and provides proper motions with a typical accuracy of 4 mas/yr. Consequently, we used a subset of the Tycho objects also listed in the PPM catalogue as our primary reference frame. On our first astrometric plate (left panel in Fig. 1), 19 Tycho stars in common with the PPM define the primary reference, while a grid of 17 fainter stars is used as the secondary reference frame. This grid of fainter stars acts as the "primary reference frame" on the plates taken with the 105 cm astrometric reflector, defined as step 2 in Table 1. The procedure is then repeated to transfer the reference frame from step 2 to step 3, from 3 to 4, and from 4 to 5, ending with a grid of reference stars suitable for the calibration of the WFPC2 frame (right panel of Fig. 1). The optical and mechanical design of the OATo astrometric telescopes minimizes optical distorsions over fields of view even larger than the present ones. Indeed, no plate modeling residual effects (see i.e. Chiumiento et al, 1991; Lattanzi et al, 1991) can be seen in our data.

The geometric distosions in HST/PC data have been corrected following the standard procedure described in Holtzmann et al (1995). The accuracy of our procedure can be evaluated from the values of ϵ_r, the star centering errors which are typical of each telescope/detector combination, and ϵ_{tr}, the errors due to the least square procedure used to generate the secondary stars grid. These are also given Table 1.

The resulting position of Geminga at epoch=1995.21 is $\alpha = 6^h33^m54.1530^s$, $\delta = 17^o46'12.909$"; these coordinates are in the Hipparcos reference frame and, therefore, in the ICRS.

To this value we attach the error $\sqrt{\epsilon_{HST}^2 + \epsilon_{sys}^2 + \epsilon_{Tycho}^2}$, where

• ϵ_{HST} is the centering error ϵ_r of the HST image, which is conservatively taken as 1/10 pixel (0."005);

Table 1. The stars in the secondary grid of step n (5th column) become the primary grid of step n + 1 (4th column). Since some of the secondary grid stars measured at step n could not be satisfactorily measured on the image of step n+1 (owing to, e.g., saturation, duplicity, etc.) the numbers in the two columns can be different. For each step we also give the centering (ϵ_r) errors as well as the uncertainties arising from the frame transfer procedure (ϵ_{tr}). The limiting magnitude for each frame is listed in the last column. The value given for step #4 refers to the stack of 10 frames of 15 minutes, each of them providing a limiting magnitude of 24.5 The values for step 5 are educated guesses and not direct estimates, as for the other data.

step [N. images]	telescope/detector	field of view [epoch]	primary grid	secondary grid	ϵ_r	ϵ_{tr}	*mag*
step 1 2	OATo 38cm refractor plate, 30"/mm	70' x 70' [1984.19]	19 Tycho/PPM	17	0".102	0".044	14
step 2 2	OATo 105cm reflector plate, 20".7/mm	30' x 30' [1984.19]	16	28	0.061	0.020	17
step 3 2	OATo 105cm reflector CCD, 0".48/px	9' x 10' [1996.13]	26	21	0.026	0.011	19.5
step 4 1	ESO NTT 3.5m, SUSI CCD 0".13/px	2.5' x 2.5' [1992.86]	16	10	0.015	0.008	26
step 5 1	HST 2.4m, PC2 CCD, 0".046/px	35" x 35" [1995.21]	10	Geminga	[0.005]	[0.003]	26
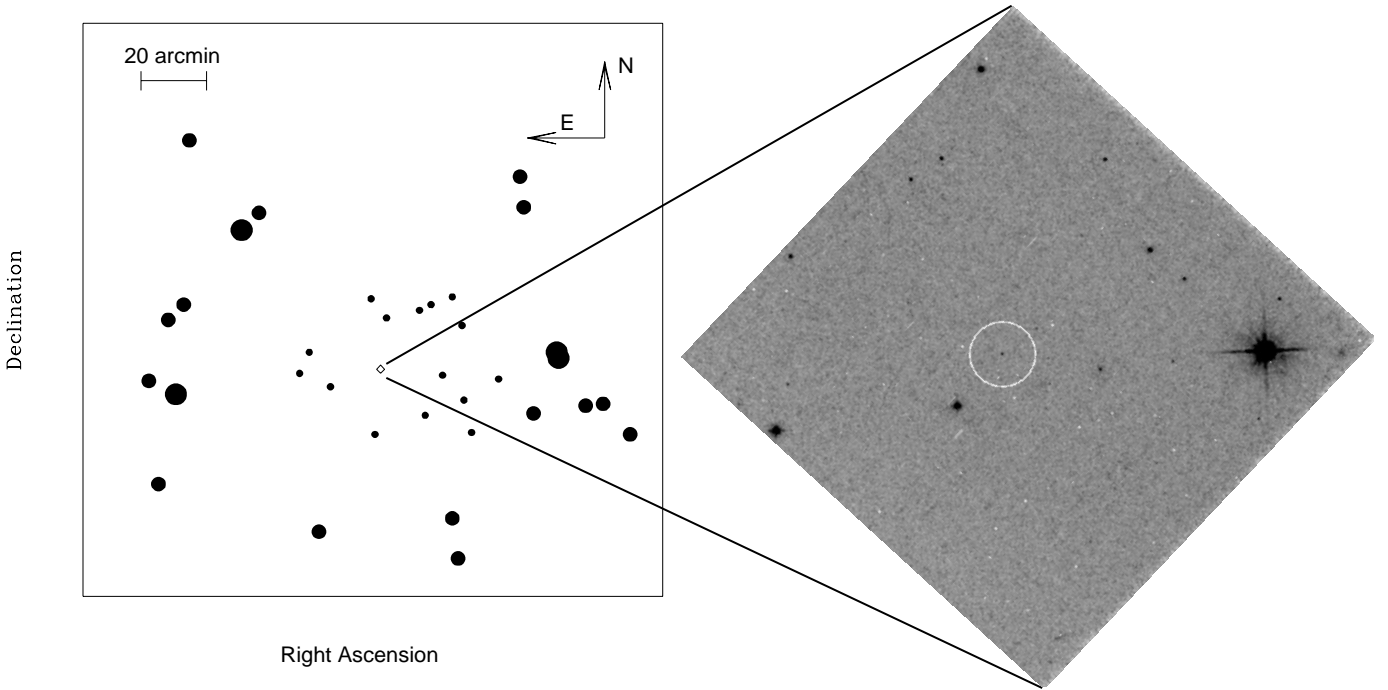
Fig. 1. Comparison between the first and the last step of our procedure. Left: schematic representation of the 70' x 70' astrometric plate taken at the OATo. Hipparcos stars are marked with large filled circles, Tycho stars with medium circles, while the small circles in the central region of the plate identify the stars used as secondary reference frame. The diamond in the center gives the position and actual dimension of the HST image, which represents the last step of our chain. Right: 35" x 35" Planetary Camera image of the field of Geminga obtained with a 4400 sec exposure through filter 555, roughly equivalent to V. Geminga is shown inside a white circle.

- ϵ_{sys} results from the combination of the errors induced by the least square adjustments used, at each step, to generate the lists of secondary stellar grids ϵ_{sys} (Eichhorn and Williams, 1963). Following (Lattanzi et al, 1997), for m stars with average centering error ϵ_r, such transformation errors can be written as $\epsilon_{tr} \sim \sqrt{3} \times \epsilon_r / \sqrt{m}$, where 3 is the number of free parameters in the linear plate-to-field transformation procedure. Table 1 gives the centering errors ϵ_r and the frame transfer ones ϵ_{tr} for each step of our procedure. Adding in quadrature the ϵ_{tr}'s one ob-

tains ϵ_{sys} 0."050. Since this procedure has been independently performed for the two images available for steps 1 through 3, a reduction of $\sqrt{2}$ is to be applied to the single solution ϵ_{sys}.

- ϵ_{Tycho} measures the precision with which we can register the ensamble of 17 stars, defining the secondary reference frame on the refractor image, relative to that realized by the 19 Tycho/PPM stars used as a primary reference on the refractor image. In our case $\epsilon_{Tycho} \sim \sqrt{3} \times \sigma_{Tycho} / \sqrt{19}$, where $\sigma_{Tycho} \simeq 0."032$ is the mean error (per coordinate) at the epoch

of the refractor plate accounting for both the average errors in the Tycho positions (15 mas for our sample) and the uncertainty on PPM proper motions propagated over 7 years. Therefore, the final error to be attached to the ICRS position of Geminga is 40 mas per coordinate.

Thus, the combined use of HST and Hipparcos yielded a 25 fold improvement in the source absolute positioning.

3. On the use of an accurate position

Among the pulsars seen in the optical or as high energy emitters, Geminga's positional accuracy becomes the best so far, better than that of the 9 magnitudes brighter Crab pulsar (Mc-Namara, 1971). This improved position, in conjunction with the HST measure of the proper motion and parallax (Caraveo et al., 1996), will allow the accurate calculation of the barycentric arrival time of all the available γ-ray data and the locking in phase over more than 20 yrs of data from three separate space missions. It will thus be possible to measure the period second derivative and, hence, the braking index $n = \ddot{\nu}\nu/\dot{\nu}^2$ of this neutron star. This quantity, expected to be 3 for magnetic dipole braking, has been only measured so far for young objects such as Crab (Lyne et al. 1988; $n = 2.5 \pm .01$), PSR 0540-69 (Guiffes et al.199; $2.8 \pm .01$), PSR 1509-58 (Kaspi et al.,1994; $n = 2.0 \pm .2$), and for the slightly older PSR 0833-45 (Lyne et al. 1996; $n = 1.6 \pm .3$).

While the results obtained for the three very young objects are not too far from the expectations, the braking index recently measured for the $\sim 10^4 yr$ Vela pulsar is definitely lower. Hence, the importance to exploit the stability of the $3 \ 10^5 \ y$ old Geminga to considerably enlarge the pulsar age sampled for braking index determination. The task is a challenging one: for a canonical braking index of 3, a $\ddot{\nu}$ of $2.7 10^{-26} s^{-3}$ is expected. This value is three order of magnitude smaller than that recently measured for Vela and 6 order of magnitude smaller than that of the Crab. However, such tiny value of $\ddot{\nu}$ is within reach of the SAS-2, COS-B and CGRO data.

What makes Geminga suitable for the measurement of the frequency second derivative? If we order known pulsars according to increasing values of $\ddot{\nu}$ (expected for a braking index of 3), Geminga does not come out prominently. Not less than 40 pulsars have hypothetical $\ddot{\nu}$ bigger than the value expected for Geminga. However, for all of them, these values are not measurable, because the errors on ν and $\dot{\nu}$ are too big. What singles out Geminga is the possibility to reduce such errors by phasing together 20 years worth of γ-ray data, now that the source positional accuracy is no longer a limiting factor. Thus, once again, Geminga appears to be in a special position amongst Isolated Neutron Stars. What matters most here is the source instrinsic stability, which made it worthwhile to devote a dedicated effort to the accurate measurement of its absolute position.

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