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Geminga, 10 Years of Optical Observations

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1. Introduction

The high energy source Geminga was discovered in γ rays about 20 years ago by the NASA satellite SAS-2 (Fichtel et al., 1975); between 1975 and 1982 the source was observed several times by the ESA COS-B satellite and, in parallel, a possible X-ray counterpart (1E0630+178) was found by the EINSTEIN Observatory (Bignami et al., 1983).

The detection of Geminga at X-ray wavelengths reduced the radius of error box by a factor ~ 300. It then became possible to search for its optical counterpart. First deep inspections of the HRI error circle (r = 4″) were done with the 3.5-m CFHT (Bignami et al., 1987) and led to the observations of three possible candidates, namely stars G, G' and G″, the last one being the fainter of the three (m_V=25.5). Later observations with the ESO 3.6-m (Bignami et al., 1988) and with the 5-m Hale (Halpern and Tytler, 1988) demonstrated that the first two were quite normal field stars while the unusual colours of G″ made it the most probable candidate for the optical counterpart of Geminga.

The high energy brightness of the source coupled with its faintness in the optical (L_X/L_{opt} > 1 000) was one of the arguments which led Bignami et al. (1983) to suggest that Geminga was an isolated neutron star, in spite of the lack of detectable radio emission.

In the 1990s, GRO and ROSAT observations greatly contributed to understanding the nature of the source. First came the detection of a 237 msec. pulsation in soft X-rays (0.1–2 Kev) by ROSAT (Halpern and Holt, 1992) soon followed by a similar discovery in γ rays by EGRET (Bertsch et al., 1992). This was immediately found also in old COS-B (Bignami and Caraveo, 1992) and SAS-2 (Mattox et al., 1992) archived data. This discovery of a common periodicity confirmed the identification between the γ and X-ray source and provided important information about the nature of the object. The observed pulsation at high energies can be explained only as due to the fast rotation of a highly magnetized isolated neutron star (B ~ 1.5 10^{12} G), up to now the only one detected through its γ/X emission but quiescent at radio wavelengths.

The evolution of the period of the X/γ pulsar, computed over a time span of about 10 years (1982–1992), provided a good measure of its period derivative ($\dot{P}$ ~ 1.09 10^{-14}sec sec^{-1}) and hence of its age (about 3–10^5 years). According to the standard relation adopted for radio pulsars ($\dot{E} = I\Omega\dot{\Omega}$) the overall energy output for Geminga is ~3 10^{34} ergs sec^{-1}. Assuming that all the rotational energy of the pulsar is converted in γ rays, an upper limit for its distance can be estimated (~ 340 pc). The actual distance to Geminga is then a function of the assumed γ ray efficiency ε_γ. For an efficiency similar to that of the Vela pulsar (ε_γ ~ 0.01) a value of 30–40 pc is found.

2. The Optical Counterpart

If Geminga is, indeed, an isolated neutron star, it should move with a high tangential velocity typical of radio pulsars (~ 100 km/sec.). This, coupled with the upper limit on the distance, could lead to a measurable proper motion of the proposed optical counterpart G″ (Bignami and Caraveo, 1992). The expected proper motion can be written as:

$$\mu = 0.2 v_{100}\, d_{100}^{-1} \text{ arcsec yr}^{-1}$$

(where v_{100} is the pulsar velocity in units of 100 km sec^{-1} and d_{100} its distance in units of 100 pc). Thus, a proper motion μ = 0.2″/year should be observed for a neutron star at 100 pc travelling at 100 km/sec.

Working with images taken in 1984, 1987 and 1992, Bignami, Caraveo and Mereghetti (1992, 1993) indeed found an overall displacement to NE corresponding to a proper motion of G″ μ = 0.17″/year. This value is fully consistent with the hypothesis that G″ is a close (d < 340 pc) neutron star.

Thus, Geminga joins the restricted group of the optically identified neutron stars including PSR0531+21, PSR0833-15 and PSR0540-69, detected as pulsating sources, and PSR1509-58 and PSR0656+14 for which a likely identification was recently reported (Caraveo et al., 1994 a, b).

New V filter images of G″ have been taken in January 1994 by G.F. Bignami and P. A. Caraveo with the ESO New Technology Telescope equipped with the SUperb Seeing Imager (SUSI). In order to reduce contamination from cosmic ray hits, the whole observation was subdivided in four exposures of

TABLE 1

Date	Telescope	Filter	Pixel size	Seeing	Exp. time
1984 Jan. 7[1]	CFHT	R	0.412″	0.9″	180 min
1986 Feb. 3[2]	5m-Hale	g	0.336″	1″.8	120 min
1987 Jan. 28[3]	ESO 3.6-m	V	0.675″	1.6″	120 min
1992 Nov. 4[4]	NTT/SUSI	V	0.13″	0.6″	150 min
1994 Jan. 11[5]	NTT/SUSI	V	0.13″	1″	80 min

[1] Bignami et al. (1987); [2] Halpern and Tytler (1988); [3] Bignami, Caraveo and Paul (1988); [4] Bignami, Caraveo and Mereghetti (1992, 1993); [5] This paper.

20 minutes each which have been later summed. For an immediate comparison between several images of the same field, taken with different telescopes and detectors (Table 1), all frames were tilted and rebinned to match exactly the same pixel scale and orientation (see caption to Fig. 1).

In order to check the displacement of G″ and to get a new measure of the proper motion, contour plots were prepared for each set of available observations. The overplot of the four images (Fig. 1), covering a period of 10 years, shows the object's proper motion to NE. This result confirms and continues the previous work of Bignami, Caraveo and Mereghetti (1992, 1993). In addition, we can now compare for the first time two sets of SUSI observations which, thanks to their finer pixel scale (0.13 arcsec/pix.), make it possible to observe clearly the proper motion of G″ even on time scales as short as one year. This is better shown in Figure 2 where the two NTT/SUSI observations of November 1992 and January 1994 are compared. The displacement of G″ over 14 months is evident, even taking into account the uncertainty in the centring of the object, which is less then 1 pixel.

For each original frame, the sky coordinates of G″ were then computed taking as a reference the pixel positions of several field stars (from 7 to 12) taken from the HST Guide Star Catalogue; the UK STARLINK programme ASTROM (available under anonymous ftp from the ST-ECF domain) was then used to compute the astrometric solution.

The coordinates of G″ computed at each epoch are listed in Table 2.

The quoted errors reflect both the uncertainty in measuring the pixel position of G″, which is about 1 pixel for each original frame, and the RMS of the astrometry fits, typically, a few hundredths of arcsecond. A linear fit to the coordinates in Table 2 was then computed to give an average annual displacement of 0.149″/year in RA and 0.109″/year in DEC (with an error of ± 0″.044) which is in very good agreement with previous results reported by Bignami, Caraveo and Mereghetti (1992, 1993). The coordinates of Halpern and Tytler were not used in the linear fit because they were not computed with the same set of standard stars, the original image not being available to us.

3. The Future

Having secured the optical identification of Geminga, the next step should be the precise measurement of the source distance, possibly through a parallax

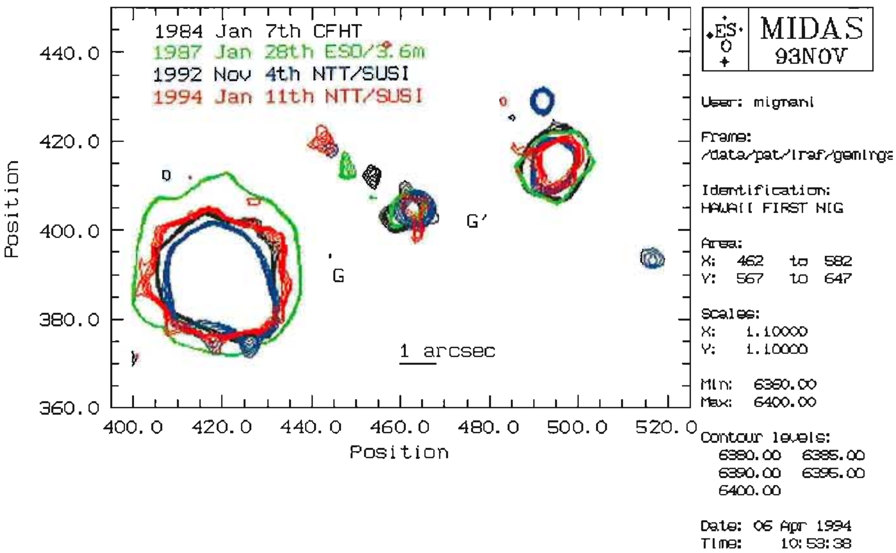

Figure 1: *Superposition of contour plots corresponding to four observations of the field of Geminga taken at various epochs and with different telescopes. The displacement of G″ over a period of 10 years appears evident (north and east are approximately to the top and to the left of the frame, respectively). All the frames were set at the same pixel scale and orientation using standard programmes in MIDAS. Given the position of at least 10 reference stars (computed with CENTER/GAUSS), linear fits to coordinate transformations were computed with ALIGN/IMAGE. As a reference we used the SUSI 92 frame because of its finer pixel scale and the better image quality (see Table 2). The coordinates of the 1984, 1987 and 1994 frames were finally corrected using REBIN/ROTATE. The final precision was very good with all the images overlapping within a few hundredths of a pixel.*

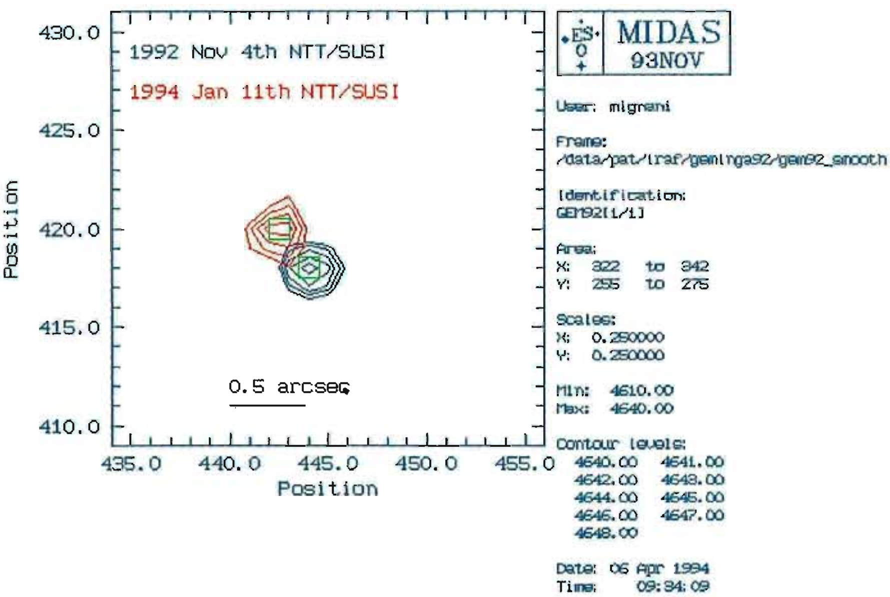

Figure 2: *A zoom of Figure 1 showing the proper motion of G″ as observed with two SUSI/NTT images taken 14 months apart. The difference in image quality is due to different seeing conditions, 0.6–0.8″ in November 1992 and about 0.9″ in January 1994 with a greater air mass.*

TABLE 2

Date	R.A. (1950)	DEC. (1950)	Error
1984 Jan. 7	$6^h30^m59^s.06$	17°48′32.7″	±0.46″
1986 Feb. 3	$6^h30^m59^s.06$	17°48′32.9″	±0.5″
1987 Jan. 28	$6^h30^m59^s.10$	17°48′33″	±0.68″
1992 Nov. 4	$6^h30^m59^s.15$	17°48′33.6″	±0.141″
1994 Jan. 11	$6^h30^m59^s.17$	17°48′33.82″	±0.144″

measurement of G″. At a distance of 100 pc the expected annual parallax would be 0.02″, a value within the capability of the WFPC2 on the Hubble Space Telescope.

This is the aim of a set of observations approved for Cycle 4. The need to pursue this programme with HST is obvious. Only the PC on board HST has the resolution (0.043″/pixel, i.e. about one third that of SUSI) required to compute the position of G″ with the necessary precision. Even if the PC field of view (35×35 arcsecs.) is smaller than that of SUSI (~ 2×2 arcmin.) it should have a number of reference stars to do accurate astrometry on the target. Exposures at the vernal and autumn equinoxes in 1994 and 1995 are foreseen.

The interest of an absolute distance measurement of Geminga would be outstanding. The optical, X and γ-ray observed fluxes could be converted accurately in luminosities, to be compared with the object's rotational energy loss, also precisely measured. This would then become the first case of a pulsar for which the energy output in each electromagnetic channel could be measured precisely as a test vs. pulsar theory.

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Jet/Cloud Interactions in Southern Radio Galaxies?

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The role of jet/cloud interactions in high redshift radio galaxies is controversial, although there can be little doubt that radio jets have a profound influence on the interstellar medium which surrounds them. Cospatial radio and optical emission-line regions, extreme emission-line gas kinematics and extended blue continuum structures may all be manifestations of this phenomenon.

The importance of jet-induced phenomena has been stressed largely from the theoretical perspective, observational support for jet-induced star formation being, at best, suggestive (e.g. van Breugel & Dey 1993). This article corrects this imbalance. We present the preliminary results of our study of the southern radio galaxy PKS2250-41, an object displaying particularly clear evidence for such an interaction.

1. Observations of PKS2250-41

We are conducting a study at ESO of low and intermediate redshift radio galaxies, such objects being sufficiently distant to show characteristics typical of high redshift galaxies, but sufficiently nearby to allow detailed study (Tadhunter et al. 1993, Morganti et al. 1993). As part of this survey, PKS2250-41 (z=0.31) was observed with the ESO 3.6-m in July 1993 using EFOSC in broad/narrow-band imaging, spectroscopic and polarimetric modes.

The narrow-band [O III] image is shown in Figure 1. The striking morphology of this object, in particular the emission-line arcs, are clearly indicative of a strong jet/cloud interaction; the west-

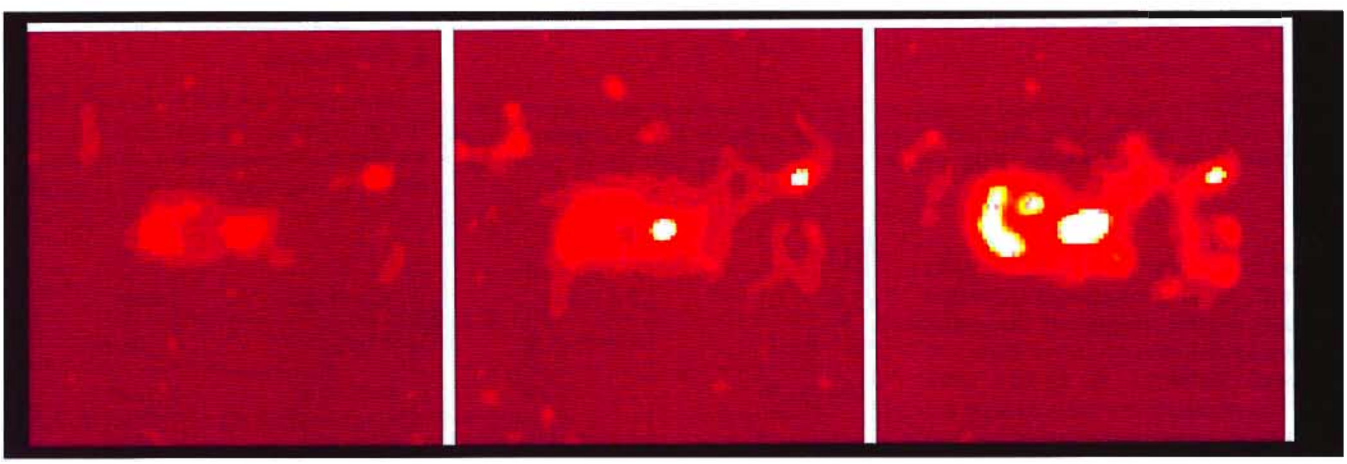

Figure 1: *A montage of 5-min B (left), 5-min V (centre) and 30-min [OIII] (λ5007 Å – right) images of a 58 arcsec square area centred on the nucleus of PKS2250-41. The images have been derived after undertaking Richardson-Lucy restoration using PSF's derived from stars on the original EFOSC frames, although all of the structure evident in these frames are also clearly seen in the original images. North is up, east to the right.*