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OBSERVATION OF A0535+26 AT ENERGIES ABOVE 150 keV WITH THE FIGARO II EXPERIMENT

G. Cusumano, T. Mineo, B. Sacco, and L. Scarsi
Istituto di Fisica Cosmica ed Applicazioni all'Informatica, CNR, via Stabile 172, 90139, Palermo, Italy
G. Gerardi
Istituto di Fisica, Universitá di Palermo, via Archirafi 36, 90136 Palermo, Italy
B. Agrinier, E. Barouch, R. Comte, and B. Parlier
CEN-Saclay, D.S.M. DAPNIA Service d'Astrophysique, 91191, Gif-sur-Yvette CEDEX, France
J. L. Masnou
UPR176, Observatoire de Paris, Section de Meudon 5, Place J. Janssen, 92195 Meudon, France
E. Massaro and G. Matt
Istituto Astronomico, Universitá "La Sapienza," via G. M. Lancisi 29, 00161 Roma, Italy
E. Costa
Istituto di Astrofisica Spaziale, CNR, via E. Fermi 21, 00044 Frascati, Italy
M. Salvati
Osservatorio Astrofisico di Arcetri, largo E. Fermi 5, 50125 Firenze, Italy
and
P. Mandrou, M. Niel, and J. F. Olive
Centre d'Etude Spatiale des Rayonnements (CNRS-UPS), B.P. 4346, 31029 Toulouse CEDEX, France
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ABSTRACT

The transient pulsating X-ray source A0535+26 was observed by the FIGARO II gamma-ray experiment on 1990 July 9. The periodogram of about 6 hr of data shows only one significant signal (3.5 σ) at the period of 103.2 s, very close to the expected one. The folded light curve is characterized by a double-peak structure and a narrow dip; it is similar to that at lower energies. The pulsed flux is $(8.6 \pm 2.3) \times 10^{-6}$ photons cm^{-2} s^{-1} keV^{-1} in the 148–260 keV band. We also find evidence of a low-energy cutoff below 167 keV.

Subject headings: gamma rays: observations — stars: individual (A0535+26) — X-rays: stars

1. INTRODUCTION

The FIGARO II (French Italian Gamma-Ray Observatory) experiment (Agnetta et al. 1989) observed the galactic anticenter region in the course of two transmediterranean balloon flights on 1986 July 11 and 1990 July 9, the main target being the Crab pulsar at which the instrument was pointing (Agrinier et al. 1990; Massaro et al. 1991). Because of its large field of view (72° × 72°), FIGARO viewed the X-ray binary A0535+26 (~5° apart) practically with the same effective area; the useful observing time was 2.5 hr and ~7 hr in the two flights, respectively. While the 1986 observation was too short to permit a useful collection of data, the longer 1990 observation allowed the first significant detection of this source in the energy interval 148–260 keV.

A0535+26 was discovered in 1975 April by *Ariel 5* (Rosenberg et al. 1975) and showed a periodicity at 104.14 ± 0.16 s indicating the presence of a highly magnetized neutron star. The optical counterpart was later identified with the Be star HDE 245770 (Li et al. 1979) allowing the classification of the source as a massive X-ray binary. The recurring behavior of the X-ray outbursts with a period of about 111 days (Priedhorsky & Terrell 1983; Motch et al. 1991) and their typical decay time of about 20 days supported the scenario of a pulsar moving in a highly eccentric orbit, powered by accretion from its massive companion; the periodic occurrences of outbursts may be correlated to the periastron passage. Two of the strongest events, however, detected in 1975 April (Rosenberg et al. 1975; Coe et al. 1975; Ricketts et al. 1975; Kaluzienski et al. 1975) and 1980 October (Frontera et al. 1985; Nagase et al. 1982; Hameury et al. 1983) were not in phase with the 111 day maxima, showing the existence of occasional intense activity. The following observations showed a general spin-up of the pulsar period with a mean rate of -1.54×10^{-4} s day^{-1}, but evidence of spin-down episodes between some of the observations has also been reported (Nagase 1989 and references therein). The history of the pulsar period is shown in Figure 1. The source characteristics are extensively described in a recent review paper (Giovannelli & Sabau Graziati 1992).

The pulse profile is not very stable either in time or in energy: it exhibits a double-peaked structure with a strong and narrow dip (Hameury et al. 1983; Frontera et al. 1985; Refloc'h et al. 1986; Sembay et al. 1990), but profiles with a single peak have also been observed (Rosenberg et al. 1975; Wilson, Fishman, & Meegan 1981). The energy spectrum is usually fitted by an exponential law (Ricker et al. 1976; Hameury et al. 1983; Sembay et al. 1990; Coe et al. 1975; Dal Fiume, Frontera, & Morelli 1988; Violes et al. 1982), with kT ranging typically from 15 to 25 keV.

At energies higher than 50 keV only a small number of data have appeared in the literature: Ricker et al. (1976) measured a flux up to 100 keV, and the highest points in the spectra given by Hameury et al. (1983), Coe et al. (1975) and Dal Fiume et al. (1988) are about at the same energy. Sembay et al. (1990) extend their spectrum up to about 200 keV with the HEXE

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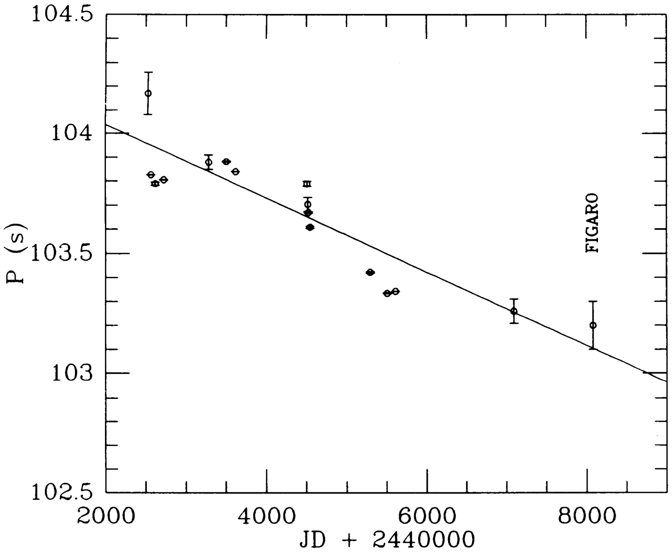

FIG. 1.—Period history for A0535+26

experiment during the spring of 1989 and noted two absorption features at 50 and 100 keV that could be interpreted as cyclotron lines.

2. EXPERIMENT AND OBSERVATION

FIGARO II is a balloon-borne gamma-ray experiment working in the energy range (0.148–4) MeV, whose technical performances have been described in Agnetta et al. (1989). The main detector is an array of nine NaI (Tl) crystal modules with a geometrical area of 3600 cm^2. It is actively shielded from the environmental background by 12 NaI (Tl) tiles along the four sides, and by four blocks of plastic scintillator at the bottom. Charged particles coming from above are anticoincided by a thin (5 mm) plastic layer on top of the experiment. The lateral tiles, 20 cm higher than the entrance window, define a field of view of 72° (FWHM). Gain variations of the main detector are continuously monitored using a low-activity ^{22}Na β^+ radioactive source, whose photons are tagged by coincidence signal from an auxiliary BGO detector. Accepted events are sent to ground by a dedicated transmitter in asynchronous mode, with a bit rate of 300 kHz. The arrival time is marked at the ground station using an atomic clock. The total timing accuracy, also considering the balloon position uncertainty, is 20 μs. The data are also recorded on-board with a time resolution of 0.1 ms. The correction of the on-board clock to achieve the absolute time of the events is performed by comparing selected sequences of data with those recorded at ground.

FIGARO II was launched from Milo (Trapani, Italy) on 1990 July 9 at 4:33 UT. The detector pointed the Crab pulsar, and, at the same time, A0535+26 ($\sim 5°$ away from Crab) from 7:06 until 14:28 UT. Because of loss of the control of the experiment due to a failure in the telecommands, the data between 11:54 and 13:30 were not used in the present analysis.

3. DATA ANALYSIS AND RESULTS

3.1. *Period Analysis*

A first-order prediction of the pulsar period was obtained by evaluating the range where it is expected at the FIGARO observation epoch. We fitted with a straight line all the values from previous observations (solid line in Fig. 1): the extrapolation, at our observation day (JD 2448081), gives (103.10 ± 0.11) s, where the error is the rms of the detected values from the fitted line.

To search for periodic signals, we apply to our data the Z_n^2 algorithm, whose statistical properties are described in detail by Buccheri & de Jager (1989) and which is defined as

$$Z_n^2 = \left(\frac{2}{N_t}\right)\sum_{j=1}^{n}\left\{\left[\sum_i N_i \cos\left(j2\pi\frac{t_i}{P}\right)\right]^2 + \left[\sum_i N_i \sin\left(j2\pi\frac{t_i}{P}\right)\right]^2\right\}, \qquad (1)$$

where N_i is the number of photons in each considered energy interval and collected between the times t_i and t_{i+1}, $N_t = \sum N_i$ is the total number of photons, P is the trial period, and n is the number of harmonics taken into account ($n = 1$ for the fundamental frequency, and so on). With this normalization the white noise power has the mean value equal to $2n$, standard deviation equal to $2(n)^{1/2}$, and the statistical distribution is that of the χ^2 with $2n$ degrees of freedom (Bendat & Pearsol 1971). In the present analysis we chose $n = 4$ because of the structured pulse shape of A0535+26, as observed at lower energies. The quantity $(Z_4^2 - 8)/4$, shown in Figure 2, represents the contribution to the signal power from the first four harmonics normalized to a zero mean value and unit standard deviation. We considered all the events, integrated every 25 ms, in the energy range (148–260) keV, corresponding to the experiment channels 23–28. The sampled period covers the interval (101–105) s, much wider than the one of the expected value, by steps of 0.1 s. The only significant feature above the random fluctuation is at (103.2 ± 0.1) s, compatible with the extrapolated value within the estimated uncertainty. Note also that the amplitude of all the remaining fluctuations is consistent with a white noise distribution. The probability to find this feature at the expected position resulted in 1.8×10^{-4}, corresponding to 3.5 Gaussian standard deviations.

A similar analysis performed at energies higher than 260 keV gave no positive detection; furthermore, no detection was obtained when the source was also outside the field of view from the low-energy data.

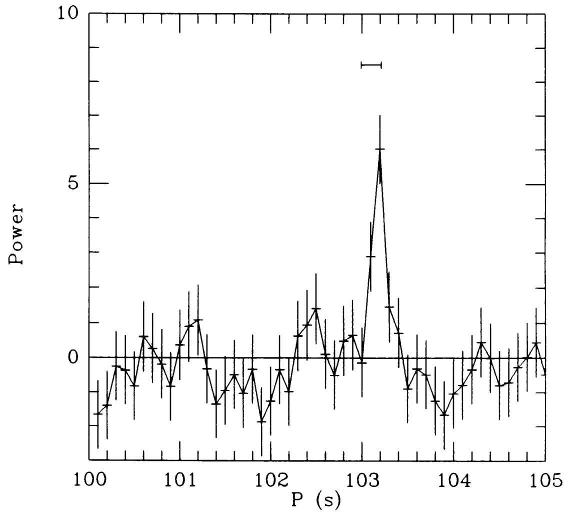

FIG. 2.—Periodogram relative to the first four harmonics in the interval 100–105 s for 5.8 hr data when A0535+26 was in the field of view of FIGARO II. The vlues of power reported in the figure are reduced at average zero and 1 σ. The range of the expected period is indicated by a horizontal bar.

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The light curve folded with the above period is given in Figure 3*b*. In the top panel the *SMM* light curve (32–91 keV) (Sembay et al. 1990) is shown for comparison (Fig. 3*a*). We stress the similarity of the main structures such as the double peak and the narrow dip; in particular, the duration of the latter feature in our data (~5 s) is very similar to that given by Fishman & Watts (1977).

From the ephemeris of Motch et al. (1991), the outburst nearest to the 1990 FIGARO observation (JD 2448081) is expected to occur 10 ± 4 days before. The orbital light curve has a typical decay time of about 20 days. The FIGARO detection, then, is compatible with a periastron outburst.

3.2. *Spectral Analysis*

The source pulsed counts are determined by subtracting the background defined as the minimum level in the light curve. Of course, any steady source component is lost in the procedure. In this particular case, since the minimum occurs in a narrow dip, the background level depends strongly on the binning. To overcome this difficulty, we computed a template light curve in the energy interval (148–260) keV, by using the Fourier coefficients of the first four harmonics, and adopted the value of the template minimum (dashed line in Fig. 3*b*).

The total pulsed flux in the band (148–260) keV obtained by the response matrix of the FIGARO II detector (Agnetta et al. 1989) is $(8.6 \pm 2.3) \times 10^{-6}$ photons $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$; the spectral distribution is shown in Figure 4. Note that no statistically significant flux ($[3.6 \pm 4.2] \times 10^{-6}$ photons $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$) was obtained at the lower energy point (148–167 keV), corresponding to the experiment channel 23. The above errors of the flux values take into account the indetermination of the adopted template light curve in addition to the statistical contribution. The light curve of the events in channel 23 with the corresponding background level is shown in Figure 3*c*: it is compatible with a constant count rate different from the higher energy range. We stress that the energy interval (148–167) keV is unaffected by possible instabilities in the energy threshold position, which was fixed in the lower channel 22. We therefore conclude that the energy spectrum of the source really shows a dip around (150–160 keV), with the flux upper limit observed well below the positive detections of the neighboring higher energy bins. As a further check we considered the deconvolved spectrum of the Crab pulsar, observed simultaneously with A0535+26: here channel 23 is perfectly aligned with the power-law fit. A power-law extrapolation from the higher energy points would give an expected flux equal to $(3.6 \pm 1.1) \times 10^{-5}$ photons $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$, that is 2.8 σ greater than the measured one. Of course, this figure is only indicative because the actual spectral shape in this band is unknown.

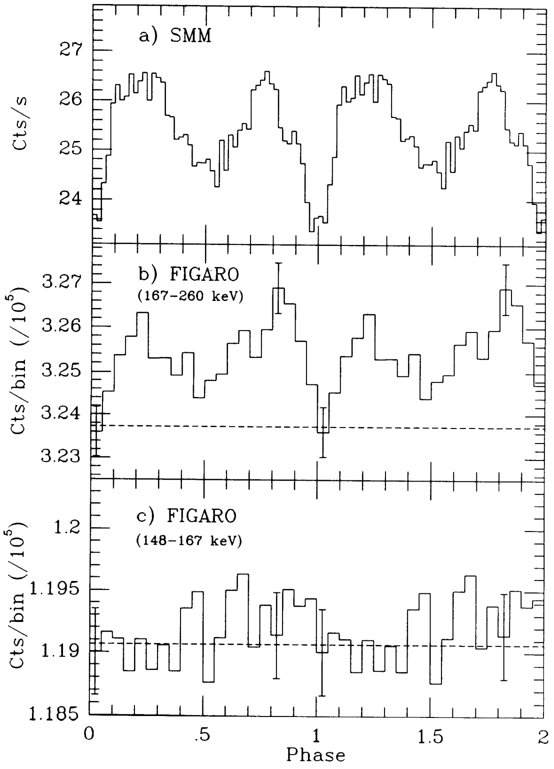

FIG. 3.—Light curve of A0535+26 in the energy range (32–91) keV as observed by *SMM* (Sembay et al. 1990) (*a*) and those obtained from the FIGARO data at 103.2 s in the energy ranges (167–260) keV (*b*) and (148–167) keV (*c*). The dashed lines indicate the background levels as derived from the template light curve and used to compute the pulsed flux.

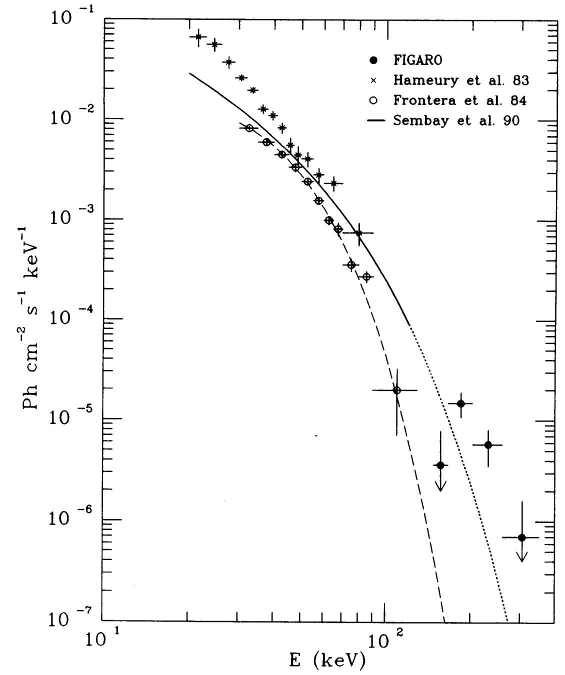

FIG. 4.—Spectrum of the pulsed emission of A0535+26 in the low-energy gamma rays as measured by FIGARO. Data from previous hard X-ray measurements, both pulsed (Frontera et al. 1984) and total (Hameury et al. 1983) are also shown; the solid line is the spectrum given by Sembay et al. (1990).

4. DISCUSSION

Figure 4 shows several spectra of A0535+26 in outbursts obtained at different epochs. The data of Frontera et al. (1984) are relative only to the pulsed flux such as ours, while the other data include also the nonpulsed component. Despite the variability of the source, the outburst spectra fall within a factor of a few from each other, and it is not misleading to consider them together with our results. The $E < 100$ keV data have usually been represented in terms of optically thin thermal bremsstrahlung with kT up to ~25 keV; Frontera et al. (1984) and Dal Fiume et al. (1988) found that a Wien spectrum better fits the data points with kT equal to 7.68 and 9.1 keV for the total and pulsed flux, respectively. In any case, our points are significantly above the extrapolations of these spectra at energies $E \geq 150$ keV, and therefore, if these representations have a physical reality, our measurements require a separate component.

It has been suggested, however, that the medium-energy cutoff might be related with a cyclotron frequency rather than a thermal energy. Evidence of absorption features has been found in the data collected during the 1989.3 outbursts (Kendziorra et al. 1991); these features fall at 50 and 100 keV and can be interpreted as the first and second harmonic in a field of 4.3×10^{12} G. Our low-energy cutoff would then correspond to the blue shoulder of the third harmonic, and one would predict a measurable flux at energies between 110 and 140 keV. Other observers have found no evidence of spectral features of any kind at $E \leq 80$ keV; in particular, Frontera et al. (1985), also on the basis of the increase of the pulsed fraction with energy, suggest that the medium-energy cutoff is due to resonance cyclotron absorption in a 9×10^{12} G field. In this alternative scenario, our observations would indicate an absorption feature in the energy range from 90 to 150 keV.

The issue is obviously important for the transfer problem in the pulsar magnetosphere—see, for instance, Meszáros & Nagel (1985a, b) and Harding & Preece (1987)—and can be addressed directly by wide-band OSSE-GRO observations in the immediate future.

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