OBSERVATION OF PULSED HARD X-RAYS/ γ -RAYS FROM PSR 1509–58

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ABSTRACT

We observed a young rotation-powered pulsar, PSR 1509–58, in the hard X-ray/ γ -ray or the soft γ -ray band with a balloon-borne detector in Brazil on 1991 November 19 (UT). With a timing analysis we detected pulsations in the energy band 94–240 keV at the 150.687 ms period determined from radio observations. The pulsating flux is $(7.1 \pm 1.7) \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ in this band, and the energy spectrum follows a power law with photon index $\alpha = 1.64 \pm 0.4$. The averaged pulse profile shows a broad single peak with a sharp rise and has a duty cycle around 50% or higher: these features are similar to what have been observed in the X-ray band by the *Ginga* satellite.

Based on the data available now, the fraction of energy transformed from rotational energy loss to pulsed/nonpulsed soft γ -ray radiation is estimated. If the solid angle swept by the pulsed beam is about the same as for the Crab pulsar (PSR 0531+21) and the Vela pulsar (PSR 0833–45), PSR 1509–58 turn out to be an extremely efficient pulsar, converting a large fraction of its rotational energy loss to radiation, as the outer gap model predicts. The observed pulsed spectrum, however, is strong in the soft γ -ray band, in a sharp contrast to what has been observed in the Vela pulsar, a pulsar expected to be similar PSR 1509–58 in the outer gap model.

The fact that the pulse profile remains broad and single-peaked in the soft γ -ray band is also new for Crab-like pulsars. In these regards, PSR 1509–58 may require some alteration to the standard outer gap model or even a new model for gamma-ray emission in pulsars.

Subject headings: gamma rays: observations — pulsars: individual (PSR 1509–58) — X-rays: stars

1. INTRODUCTION

PSR 1509–58 is young rotation-powered (Crab-like) pulsar whose pulsation ($P = 150.7$ ms) was first detected in the X-ray band by the *Einstein Observatory* (Seward & Harnden 1982) and shortly afterward in the radio-wave band by Manchester, Tuohy, & D'Amico (1982). Since then several observational studies have been made on PSR 1509–58: braking index has been measured to be the largest ($n = 2.83$) among known rotation-powered pulsars (Manchester, Durdin, & Newton 1985); the absolute time at which the pulse starts has been compared in the radio-wave and X-ray bands (Kawai et al. 1991); and a possible record of the supernova explosion that produced the pulsar and its associated nebula (MSH 15–52) has been found in an old Chinese literature (Thorsett 1992).

Since the discovery of the first pulsar, many important observations have been made and new theories have evolved thereon. Nonetheless the radiation emission mechanism in the rotation-powered pulsar is not yet coherently understood (see, e.g., Arons 1990; Michel 1991). A successful pulsar model is warranted only if it explains the existence of the observed variety of rotation-powered pulsars. In this respect, we consider the study on PSR 1509–58 to be particularly important because its magnetic field is highest among the few well-studied pulsars, and its X-ray pulse profile is uncommon to other young pulsars. We note here that the surface magnetic field (B) is calculated from the rotational energy-loss rate due to magnetic dipole radiation. The value, $B \sim 3 \times 10^{13} \text{ G} = 0.68 B_c$ (Table 1) comes out if a formula given by Shapiro & Teukolsky (1983, p. 278) is used: here B_c is the critical magnetic field at which the energy spacing of the Landau levels of cyclotron motion reaches the electron rest mass, $B_c \equiv m^2 c^3 / e \hbar$.

The pulsating X-ray spectrum of PSR 1509–58 was recently measured up to 60 keV by the *Ginga* satellite (Kawai, Okayasu, & Sekimoto 1993). The average pulse profile shows one broad peak in the X-ray band (2–11 keV) (Kawai et al. 1991), while it is known to have one sharp peak in the radio band (at 1.4

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TABLE 1
CHARACTERISTICS OF SELECTED ROTATION-POWERED PULSARS^a

Parameter	PSR 0531+21	PSR 1509–58	PSR 0833–45	PSR 1706–44	Geminga
P (ms)	33.4	150.7	89.3	102.4	237.1
$\dot{P}$ (s s^{-1})	4.21×10^{-13}	1.54×10^{-12}	1.25×10^{-13}	9.34×10^{-14}	1.14×10^{-14}
E_{rot} (ergs) ^b	1.77×10^{49}	8.70×10^{47}	2.48×10^{48}	1.88×10^{48}	3.51×10^{47}
$\dot{E}_{\text{rot}}$ (ergs s^{-1}) ^b	-4.46×10^{38}	-1.77×10^{37}	-6.91×10^{36}	-3.43×10^{36}	-3.38×10^{34}
Age (yr) ^b	1260	1550	11400	17400	330000
Braking index	2.51 ^c	2.83 ^d	...	...	...
Distance (kpc)	2.0 ^e	4.2 ^e	0.5 ^e	1.5 ^f	...
B (G) ^b	6.6×10^{12}	3.1×10^{13}	6.8×10^{12}	6.3×10^{12}	3.3×10^{12}

^a The moment of inertia I and the radius of the neutron star were assumed to be 10^{45} g cm^2 and 10^6 cm, respectively, in the calculations.

^b Calculated based on the formula given in Shapiro & Teukolsky 1983.

^c Taken from Groth 1975.

^d Taken from Manchester et al. 1985.

^e Taken from Seward 1985.

^f Quoted in Thompson 1992.

GHz) (Manchester et al. 1982). When the pulse timing in the two bands are compared, the X-ray pulse rises with a delay in phase of ~ 0.25 relative to the radio pulse (Kawai et al. 1991). The measured pulsed flux follows a power law with an index $\alpha = 1.30 \pm 0.05$ (Kawai et al. 1993) significantly harder than that of the Crab pulsar ($\alpha \sim 2$). These characteristics are quite different from what is known about the Crab pulsar and the Vela pulsar (see, e.g., Lyne & Graham-Smith 1990).

It has been pointed out that the age (~ 1500 yr) of PSR 1509–58 is much less than that ($> 10^4$ yr) of MSH 15–52 (Clark & Caswell 1976; Seward et al. 1983; Lyne & Graham-Smith 1990). There is an argument that PSR 1509–58 may be a neutron star that had been born with a weak magnetic field and built up its magnetic dipole moment with time in the past (e.g., Seward and Wang 1988).

Among many models of rotation-powered pulsars and their X-ray/ γ -ray emission mechanism, we will refer to the outer gap model by Cheng, Ho, & Ruderman (1986a) when we compare PSR 1509–58 with the Crab pulsar and the Vela pulsar. In the present paper, we refer to this model as the CHR outer gap model. We believe that other models probably give similar predictions as long as high-energy radiation is assumed to come from the acceleration region along the last open field line near the light cylinder (see, e.g., Arons 1990). The CHR outer gap model has been worked out in detail to give an overall description of the magnetosphere and the radiation mechanism in the Crab-like X-ray/ γ -ray pulsars. The model has been applied to account for various observations on the Crab pulsar and the Vela pulsar (Cheng, Ho, & Ruderman 1986b) and to predict the evolutionary path of the Crab-like γ -ray pulsars (Ruderman & Cheng 1988). Up to now, there has not been any overall consistent theory for gamma-ray emission from rotationally powered pulsars (Arons 1990; Michel 1991) and the CHR outer gap model is no exception (Cheng et al. 1986a).

Recently, Halpern & Holt (1992) detected pulsed X-ray emission with a period of 237 ms from Geminga (2CG 195+4, 1E 630+178) using *ROSAT* data. Subsequently the periodic emission was found by EGRET on the *Compton Gamma-Ray Observatory* (Bertsch et al. 1992). The period derivative determination by EGRET in turn allowed the detection of the pulsed emission in the *COS B* data accumulated between 1975 and 1982 (Bignami & Caraveo 1992) and in the *SAS 2* data taken in 1972–1973 (Mattox et al. 1992). The Geminga pulsar

differs from other Crab-like pulsars in that it expends most of the rotational energy loss as high-energy γ -rays but almost none as X-rays. This feature of the Geminga pulsar as well as the twin-peak pulse structure of the high-energy emission seems to fit into the predicted evolutionary path of rotation-powered pulsars (Ruderman et al. 1993).

The present observation is the first to extend the spectral measurement of the pulsed emission from PSR 1509–58 to the hard X-ray or soft γ -ray band (≥ 60 keV). If the spectrum extends from the *Ginga* energy band upward with the same photon index ($\alpha = 1.30$), the pulsed radiation exhausts the total rotational energy loss before reaching 50 MeV (we assume about half of the 4π solid angle is swept with the observed flux). Therefore, there must be a break in the spectral shape in the soft γ -ray band. Depending on where the break occurs, PSR 1509–58 may turn out to be a peculiar pulsar emitting a large fraction of radiated energy as pulsed hard X-rays or soft γ -rays, not as pulsed high-energy γ -rays as in the Vela pulsar.

Concerning the pulse profile, Kawai et al. (1991) point out a possibility that the broad X-ray peak may consist of two unresolved components. In general, outer gap models predict the pulse profile to have a twin-peak structure in the high-energy band like those observed in the Crab and the Vela pulsars. In the soft γ -ray band, such a structure may emerge.

2. DETECTOR

The detector system used in the observation consists of 64 “well-type” phoswich counters made of $\text{Gd}_2\text{SiO}_5:0.5\%\text{Ce}$ (GSO) and CsI(Tl) (Kamae et al. 1992; Murakami et al. 1992) and 36 anticounters made of CsI(Tl) . We refer to this detector as Welcome-1. The detector characteristics relevant to the present observation are (Gunji et al. 1992; Takahashi et al. 1992): energy range, 47–710 keV; geometrical area, 740 cm^2 ; full peak efficiency, 98% at 122 keV and 30% at 511 keV; field of view (HWHM), 7.7° at 122 keV and 9.1° at 511 keV. A series of observations have been made with Welcome-1 including the one that set an upper limit on the ^{57}Co line flux from SN 1987A (Gunji et al. 1992) and measurements on the soft γ -ray spectra of Cen A and GX 339–4.

The data-taking electronics was the same as described in the previous paper (Gunji et al. 1992), except for addition of an electronic circuit to hold off data-taking after large-energy depositing events ($E \geq 60$ MeV). This was done to suppress

false events electronically generated when the amplifier system approached or passed the saturation point by heavily ionizing charged particle incidences. The hardware dead time caused by this hold-off was 1.1 ms or 400 μ s depending on whether the preamplifier did or did not saturate. The energy calibration and the effective live time were constantly monitored by using ^{152}Gd α -decays.

The detector is characterized by its ability to suppress background counts. In the energy range between 100 and 300 keV, the signal-to-noise ratio for the Crab nebula and pulsar is 1.2/1.0 after the signal has been attenuated to $\sim 40\%$ – 50% by the atmosphere remaining at balloon altitudes.

For accurate absolute timing analysis, we installed a quartz clock ($\Delta f/f = (2-3) \times 10^{-9}$) aboard the detector and a Rubidium clock on the ground base. The quartz clock was calibrated by the Rubidium clock to 1 μ s. The Rubidium clock was in turn calibrated to the UT time given by the Global Positioning System (GPS) satellites to 2 μ s.

3. OBSERVATION

The detector system (Welcome-1) was launched from the balloon base of Instituto Nacional de Pesquisas Espaciais (INPE) in Cachoeira Paulista, São Paulo, Brazil ($45^{\circ}00'34''\text{W}$, $22^{\circ}39'44''\text{S}$), at Brazilian Local Time (BLT) 23:55, 1991 November 18. The detector reached the ceiling altitude of 36.5 km (4.77 g cm^{-2}) and observation of PSR 1509–58 started at 11:05, 1991 November 19 (BLT). We observed PSR 1509–58 and collected data on it for ~ 9420 s. In the middle of the observation, two off-source observations (15 minutes long and 10 minutes long) were inserted. Prior to the present measurement, we observed the Crab nebula/pulsar, the Vela pulsar, and Cen A.

Pointing was done by combination of a geomagnetic sensor and an azimuthal motor (the azimuth), and, a clinometer and an elevation motor (the elevation). The detector direction was monitored to about $\pm 1^{\circ}$ by imaging the Sun with a wide-view CCD camera. The detector was rotated in azimuth every 5 minutes and the mean angular offset of PSR 1509–58 from the center of F. O. V. was $\sim 3^{\circ}$, while the mean elevation angle of the telescope was $\sim 52^{\circ}7$.

In the observation, the energy, the pulse-shape-discrimination gate, the hit-pattern of neighboring counters, and the arrival time of each γ -ray were recorded. The arrival time was referenced to the on-board quartz clock. The overall accuracy of timing measurement in UT was $\sim 2 \mu$ s during the observation.

4. DATA ANALYSIS

As in the previous flight (Gunji et al. 1992), we rejected events with one or more hits in the most and second-most adjacent layers of counters to eliminate Compton-scattered γ -rays, nuclear-reaction induced γ -rays, and other signals associated with one or more extra hits in neighboring counters. The improvement to reject electronically generated false events described in § 2 turned out to be effective in removing most false events, but not completely: for some large pulses preamplifiers took longer than the fixed 1.1 ms to recover. In rare cases hits in the CsI(Tl) pass through the pulse shape discriminator when the preamplifier has not recovered to normal. In such cases, several hits are registered in a train in counters where a heavily ionizing particle passed through. We rejected events, in the off-line analysis, when another event existed in

the same or adjoining phoswich counters within 1 ms to eliminate such false events entirely.

The entire event selection procedure reduced the total observation time from 9420 to 7150 s (efficiency of 75.9%) for 63 counters: one counter was not operational. The background counting rate was similar to that measured in our 1990 flight (Gunji et al. 1992): $4.75 \times 10^{-2} \text{ counts cm}^{-2} \text{ s}^{-1}$ (47–710 keV). The spectrum after the event selection was well reproduced by the sum of the measured internal background due to radioactive contamination in the detection part (Takahashi et al. 1992) and what is expected from the atmospheric and celestial diffuse radiation given by Gehrels (1985).

The overall electronic gain was calibrated continuously for every counter by using the α -decay of ^{152}Gd in GSO. To follow time variation at fine steps and yet to keep high statistical accuracy, the pulse-height spectrum of ^{152}Gd α -decay events were accumulated for 30 minutes centered around time bins set at 5 minutes intervals. This procedure eliminated overcompensation of statistical fluctuations in the gain adjustment procedure. The resultant time variation of the overall gain is consistent with what is expected from the measured dependence of the GSO light yield and the phototube gain on temperature, as well as the measured dependence of the phototube gain on its orientation to Earth's magnetic field.

The measured arrival times of event-selected soft γ -rays in the energy range between 94 and 240 keV were converted to the barycentric time by using the computer program supplied by Deeter (1992). They were then folded into five pulse-phase bins at trial periods around the period predicted for the time of observation by Princeton Pulsar Catalogue (Johnston et al. 1992) (Table 2). Chi-squares (χ^2 's) were calculated as a function of trial period by assuming a flat structureless time profile (periodogram). The periodogram obtained is shown in Figure 1.

The period that gives the highest reduced chi-square is 150.687 ms with total χ^2 of 21.8 for 4 d.o.f. (reduced χ^2 of 5.45). This is in perfect agreement with the prediction $P = 150.6874$ ms based on the radio observation at barycentric epoch $t = 48579.605$ MJD (Johnston et al. 1992).

The data obtained in our observation were folded at the predicted period $P = 150.6874$ ms starting from $t = 48579.605$ MJD. The starting time turned out to be at phase 0.32 while the peak of the radio pulse for this epoch is predicted to be at phase 0.65. The averaged pulse profile between 94 and 240 keV is shown in Figure 2, together with that obtained with *Ginga* (Kawai et al. 1991). Figure 2 demonstrates the detection of the pulsed soft γ -ray flux from PSR 1509–58. The two pulse profiles were aligned relative to the predicted radio peak at the

TABLE 2
PARAMETERS FOR PSR 1509–58*

Parameter	Value
R.A. (J2000) (α)	$15^{\text{h}}13^{\text{m}}55^{\text{s}}.656$
Decl. (J2000) (δ)	$-59^{\circ}08'09''.09$
Frequency (s^{-1}) (ν_0)	6.6375697299830
First derivative (s^{-2}) ($\dot{\nu}_0$)	-6.76954×10^{-11}
Second derivative (s^{-3}) ($\ddot{\nu}_0$)	1.96×10^{-21}
Phase zero at the solar system barycenter (M. J. D.) (t_0)	48355.000000000
Radio peak at the geocenter (M. J. D.) (t_{radio})	48355.000000507

* The first five parameters are given at the barycentric epoch t_0 (Johnston et al. 1992).

FIG. 1.—Periodogram for PSR 1509–58 obtained by folding the event arrival time into five bins with various trial periods.

time of respective observation: the phase difference between them is $\Delta\phi = -0.02^{+0.04}_{-0.02}$ and both pulses are led by the radio pulse by 0.25 phase. The pulse profile is also similar in the X-ray and soft γ -ray bands: we do not see any hint of sharp peaks emerging in the soft γ -ray profile, although this conclusion is somewhat limited by statistics.

To check the overall instrumental accuracy we observed the Crab pulsar in the same flight. The measured pulse period is 33.3974 ms at barycentric epoch of 48,579.249 MJD, in agreement with the predicted period of 33.39739 ms (Arzoumanian, Nice, & Taylor 1992). The measured pulse profile and pulse flux are also consistent with previous publications (Graser & Schönfelder 1982).

We also folded the data taken during the off-source observations (total 1620 s before dead time corrections) conducted in the middle of the PSR 1509–58 observation, at around the period $P = 150.6874$ ms. The maximum reduced χ^2 among

FIG. 2.—Pulse profiles for PSR 1509–58 obtained in our hard X-ray/ γ -ray observation in the energy range between 94 and 240 keV (lower panel) and by *Ginga* in the energy range between 2 and 11 keV (upper panel; Kawai et al. 1991).

those for 180 trial periods was 3.15 for 4 d.o.f.: it occurred at a period off the predicted one for PSR 1509–58. The maximum χ^2 is consistent with its being accidental.

In order to estimate the flux of the pulsed component, we fitted the measured pulse profile in each energy band with a pulse profile template. The template fixed the pulse shape, and the amplitude and the nonpulsating background level were adjusted in fitting the observed time profile. The area enclosed under the template gives the flux of the pulsed component, while the nonpulsating background level contains the nebula contribution and the background radiation. We used the pulse shape obtained in the X-ray band (2–11 keV) by *Ginga* as the template (Kawai et al. 1991). The measured pulse profiles and the best-fit pulse shapes are shown for seven energy bins in Figure 3.

The energy spectrum of the pulsating flux from PSR 1509–58 is consistent with a single power law: a fit gives the photon index $\alpha = 1.64^{+0.43}_{-0.42}$ and a flux of $(1.11 \pm 0.28) \times 10^{-5}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ at 100 keV (Fig. 4). This spectrum is consistent with the X-ray spectrum by *Ginga* both in slope and in absolute flux.

To determine the absolute phase of the soft γ -ray pulse, we searched for the best fit by shifting the template in phase. The best fit gives the phase difference between the pulse profiles of *Ginga* and ours to be $-0.02^{+0.04}_{-0.02}$. We also tried a somewhat broader shaped template, but the spectrum and the pulse phase came out statistically consistent with what have been obtained with the *Ginga* template.

We failed to detect the nonpulsed flux from the nebula (MSH 15–52) containing PSR 1509–58 by the on-source/off-source subtraction in our energy range. The nonpulsed flux has been detected in the X-ray band 2–60 keV (Trussoni et al. 1990; Kawai et al. 1993). The total luminosity in the energy range 2–710 keV will be $L = 9.4 \times 10^{35}$ ergs s^{-1} if the power-law spectrum ($\alpha = 2.15$) determined by *Ginga* (Kawai et al. 1993) extends to this energy range.

FIG. 3.—Pulse profiles for PSR 1509–58 in seven energy bins. The curve and line represent the best fit for the *Ginga* template.

FIG. 4.—Measured pulsed spectrum from PSR 1509–58 between 47 keV and 710 keV obtained in our observation (plots with error bars). The solid line shows the best-fit single power-law spectrum obtained on our data (index $1.64^{+0.43}_{-0.42}$). The dotted line shows the extrapolation of the best fit single power-law spectrum obtained with *Ginga* (index 1.30 ± 0.05 , Kawai et al. 1991). The 2σ upper limits obtained with *HEAO-3* (Ulmer et al. 1991) are shown by circles with arrows.

5. COMPARISON WITH OTHER ROTATION-POWERED PULSARS

The power of the pulsed flux of PSR 1509–58 in the X-ray/ γ -ray band is compared with that of other rotation-powered pulsars in Table 3. Similar comparative studies have been done in the soft X-ray band or below (Pacini & Salvati 1987; Seward & Wang 1988) and in the high-energy γ -ray band (Ruderman & Cheng 1988; Ruderman et al. 1993).

The luminosity L in the energy range between E_1 and E_2 for a power-law spectrum is

$$L = 4\pi D^2 \eta \int_{E_1}^{E_2} K \left(\frac{E}{E_0} \right)^{-\alpha} E dE, \quad (1)$$

$$\eta = \frac{\Theta}{4\pi}. \quad (2)$$

Here K is the photon flux at energy E_0 , D is the distance from Earth to the object, Θ is the “effective” solid angle in which pulsating radiation sweeps across, and η is the solid angle factor. In general, the time-integrated pulsed flux varies over the solid angle, the effective solid angle Θ is defined to be the quotient of the total pulsed flux divided by the flux per steradian observed on earth. The effective solid angle Θ is assumed to be 4π for the nebula component ($\eta = 1$).

For the Crab pulsar (PSR 0531+21), Chiang & Romani (1992) predict the solid angle Θ to be $\sim 0.6 \times 4\pi$ or η to be ~ 0.6 for the CHR outer gap model. They have also calculated

TABLE 3
HIGH-ENERGY EMISSION OF ROTATION-POWERED PULSARS

Parameter	PSR 0531+21	PSR 1509–58	PSR 0833–45	PSR 1706–44	Geminga
P (ms)	33.4	150.7	89.3	102.4	237.1
$\dot{P}$ ($s s^{-1}$)	4.21×10^{-13}	1.54×10^{-12}	1.25×10^{-13}	9.34×10^{-14}	1.14×10^{-14}
B (G) ^a	7.6×10^{12}	3.1×10^{13}	6.8×10^{12}	6.3×10^{12}	3.3×10^{12}
$\dot{E}_{rot}$ (ergs s^{-1}) ^a	-4.46×10^{38}	-1.77×10^{37}	-6.91×10^{36}	-3.43×10^{36}	-3.38×10^{34}
L_1^b (nebula)	2.5×10^{37c}	$< 9.4 \times 10^{35d}$	...	...	...
$(L_1/\dot{E}_{rot})$	(5.5%)	(<5.2%)	...	...	...
L_1^b (pulsar)	$3.5 \times 10^{36}\eta^e$	$1.6 \times 10^{36}\eta^f$	$< 2.5 \times 10^{33}\eta^g$	$< 2.3 \times 10^{34}\eta^h$	...
$(L_1/\dot{E}_{rot})$	(0.77%)	(9.0%)	(<0.036%)	(<0.66%)	...
L_2^i (nebula)	2.6×10^{37c}	$< 9.8 \times 10^{35d}$	...	...	...
$(L_2/\dot{E}_{rot})$	(5.8%)	(<5.4%)	...	...	...
L_2^i (pulsar)	$3.7 \times 10^{36}\eta^e$	$< 1.9 \times 10^{36}\eta^j$	$< 4.5 \times 10^{33}\eta^g$	$< 2.5 \times 10^{34}\eta^h$	...
$(L_2/\dot{E}_{rot})$	(0.82%)	(<10%)	(<0.065%)	(<0.74%)	...
L_3^k (nebula)	4.7×10^{36c}	$< 4.3 \times 10^{35d}$	...	...	...
$(L_3/\dot{E}_{rot})$	(1.0%)	(<2.4%)	...	...	...
L_3^k (pulsar)	$2.2 \times 10^{36}\eta^e$	$< 4.5 \times 10^{36}\eta^j$	$2.0 \times 10^{35}\eta^l$	$1.9 \times 10^{35}\eta^m$	...
$(L_3/\dot{E}_{rot})$	(0.50%)	(<25%)	(2.9%)	(5.5%)	...

^a The moment of inertia I and the radius of the neutron star are taken to be 10^{45} g cm^2 and 10^6 cm, respectively.

^b L_1 ; Calculated for the energy range between 2 and 710 keV.

^c Calculated based on the results given by Jung 1989 (between 2 and 50 keV) and by Graser & Schönfelder 1982 (between 50 keV and 2 GeV).

^d Calculated based on the result of Kawai et al. 1993 and assuming their power-law spectrum to higher energies.

^e Calculated by using the result of Hasinger et al. 1984.

^f Calculated from our result and that of Kawai et al. 1993.

^g Calculated by using data points given in Strickman et al. 1992 (between 2 keV and 1.5 MeV) and Sacco et al. 1990 (between 0.2 and 6 MeV).

^h Calculated by assuming the power-law spectrum of Thompson et al. 1992 (between 20 MeV and 20 GeV) extended to 2 GeV.

ⁱ L_2 ; Calculated for the energy range between 2 keV and 1 MeV.

^j Calculated from our result and that of Kawai et al. 1993 for energies between 2 and 500 keV. For higher energies, our 500 keV point and the 2σ upper limit calculated from the quoted sensitivity of *COS B* (Simpson 1980; Swanenburg et al. 1981; Hermesen 1980) have been connected to give a power-law flux with the photon index of 2.1 (Fig. 5).

^k L_3 ; Calculated for the energy range between 1 MeV and 2 GeV.

^l Calculated for the energy range between 50 MeV and 2 GeV by using the result of Grenier et al. 1988.

^m Calculated for the energy range between 20 MeV and 2 GeV by using the result of Thompson et al. 1992.

and obtained a similar η for another pulsar emission model, the polar cap model. There is no estimate of the solid angle factor (η) for PSR 1509–58 or for the Vela pulsar (PSR 0833–45). We can, however, make a reasonable guess if we have a crude knowledge of the angles the magnetic dipole and the line of sight make to the rotational axis. The angular width of the fan-beam is also an important factor.

Smith et al. (1988) estimate the angle between the line of sight and the equatorial plane of the neutron star rotation to be $\sim 26^\circ$ for the Crab pulsar. The angle the magnetic dipole makes to the rotational axis has been estimated for a number of pulsars including the Crab pulsar and the Vela pulsar (Lyne & Manchester 1988; Rankin 1990), based on observation in the radio band. These estimates give the angle between the rotational axis and the magnetic dipole to be near 90° for young pulsars. The angle has been independently estimated at 86° for the Crab pulsar from the optical polarization data by Kristian et al. (1970). A new optical polarization measurement by Smith et al. (1988) gives, however, a somewhat smaller value ($\sim 54^\circ$ – 62.5°). Lyne & Manchester (1988) estimates the radio beam width to be $\sim 20^\circ$ for the Crab pulsar.

The estimates or predictions given in the above are consistent with the solid angle factor η being $\sim 60\%$ for the Crab and Vela pulsars. No such estimate or prediction has been given for PSR 1509–58.

Some ambiguities remain in the above estimate. For example, the dependence of emission intensity on the line-of-sight is not known. In the present analysis, we simply assume η to be ~ 0.6 for the Crab pulsar, the Vela pulsar, and PSR 1509–58, unless η is explicitly left in the estimate.

We now compare the observed pulsed flux of PSR 1509–58 with the Vela pulsar. In the CHR outer gap model, the flux and the spectrum can be characterized by the period P (or an equivalent such as the angular velocity) and the magnetic field at the light cylinder B_L (or an equivalent such as the surface magnetic field) (e.g., Cheng et al. 1986b; Ruderman & Cheng 1988). Pulsed X-rays/ γ -rays are primarily due to synchrotron radiation in the outer gap. If the two pulsars have similar line-of-sights and solid angle factors (η), their luminosities normalized by the rates of the rotational power loss, $L_{\text{sync}}/\dot{E}$, and their spectral break points (the critical energy of the synchrotron radiation), $\hbar\omega_c$, are to be related as

$$\frac{L_{\text{sync}}/\dot{E}(\text{Vela})}{L_{\text{sync}}/\dot{E}(1509-58)} \sim 1.0,$$

$$\frac{\hbar\omega_c(\text{Vela})}{\hbar\omega_c(1509-58)} \sim 2.4,$$

respectively.

The energy spectrum of the pulsed component for PSR 1509–58 is shown in a wider energy range in Figure 5: the *Ginga* results (2–60 keV) (Kawai et al. 1993), our results (47–710 keV), and the 2σ upper limit based on the quoted sensitivity of *COS B* (Simpson 1980; Swanenburg 1981; Hermesen 1980). If we are to make a guess about the spectrum in this range from these data, it is most likely that the power-law spectrum either breaks or turns off in the energy region somewhere above ~ 500 keV. One possibility is shown by the dashed line in Figure 5, a line generated by connecting our 500 keV point and the 2σ upper limit obtained with *COS B*. The power index of the dashed line is $\alpha = 2.1$, whereas the Crab pulsar has $\alpha = 2.2$ in the energy range 50 keV–2 GeV (Graser & Schönfelder 1982) and the Vela pulsar has $\alpha = 1.72$ in the

FIG. 5.—Measured pulsed spectrum for PSR 1509–58 in a wider energy region. Results obtained with *Ginga* and Welcome-1 are shown by a solid line and crosses, respectively. The 2σ upper limit is based on the quoted sensitivity of *COS B*. The dotted line is the extension of the power-law spectrum from the X-ray band. The dashed line was drawn by connecting the 500 keV point on the X-ray power-law spectrum and the 2σ upper limit (Simpson 1980; Swanenburg et al. 1981; Hermesen 1980).

50–300 MeV band and $\alpha = 2.12$ for the 300 MeV–5 GeV band (Greiner, Hermesen, & Clear 1988).

The luminosity of the pulsed emission is calculated to be $1.6 \times 10^{36} \eta$ ergs s^{-1} in the energy range between 2 and 710 keV for PSR 1509–58 assuming the following parameters: $\alpha = 1.30$ (*Ginga*), $K = 3.43 \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 1 keV (*Ginga* and our result), and $D = 4.2$ kpc (Seward 1985). This corresponds to $9.0\eta\%$ (5.4% for $\eta = 0.6$) of the rotational energy loss 1.8×10^{37} ergs s^{-1} (Table 3). The luminosity becomes $1.4 \times 10^{36} \eta$ ergs s^{-1} in the energy range between 2 and 710 keV if we assume α changes to 1.64 (ours) at 212 keV with $K = 3.25 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 212 keV. This corresponds to $8.1\eta\%$ (4.8% for $\eta = 0.6$) of the rotational energy loss. The energy emitted by the Crab pulsar in the energy range between 2 and 710 keV amounts to $3.5 \times 10^{36} \eta$ ergs s^{-1} or $0.77\eta\%$ (0.46% for $\eta = 0.6$) of the rotational energy loss $|\dot{E}_{\text{rot}}| = 4.5 \times 10^{38}$ ergs s^{-1} (Jung 1989) (Table 3). Here we assumed the distance to the Crab pulsar to be $D = 2.0$ kpc (Seward 1985).

In the summary of our observation (Table 3) we note that the rotational energy is efficiently transformed into soft γ -ray radiation (2–710 keV) for PSR 1509–58 ($9.0\eta\%$), more than 10 times the efficiency for the Crab pulsar ($0.77\eta\%$). Figure 6 shows the pulsar and nebula luminosities normalized with the rotational energy loss rate for the Crab pulsar and PSR 1509–58. In the figure, the top (E_2) and the bottom (E_1) of the energy band is taken to be $E_2/E_1 = 2$, and the solid angle factor η to be 0.6 in calculating the pulsed luminosity. If the measured power-law spectrum of PSR 1509–58 (index = 1.30)

FIG. 6.—Rate of energy transformation from a rotation of a neutron star into radiations. Each energy band is taken to be the same width in the logarithmic scale ($\Delta E/E = \frac{1}{3}$). The solid angle factor η is taken to be 0.6 for the pulsed luminosity. Note that the ordinates of Figs. 5 and 6 correspond to $F(\nu)$ and $\nu^2 F(\nu)$, respectively, and their power-law indices are $-\alpha$ and $2 - \alpha$, respectively.

breaks to another power-law spectrum at 500 keV which extends to 2 GeV with index = 2.1 (shown by dashed line in Figure 5), the total pulsed luminosity amounts to $37\eta\%$ (22% for $\eta = 0.6$) of the rotational energy loss, ~ 30 times the ratio for the Crab pulsar ($1.3\eta\% = 0.78\%$). This general conclusion about PSR 1509–58 does not depend much on how the spectrum changes above 500 keV, or on the power-law index below 500 keV, or on the value of η .

Pacini & Salvati (1987) and Seward & Wang (1988) have compared the X-ray (0.2–4 keV) luminosity from the nebulae and compact sources with the rate of rotational energy loss, the duty cycle, and the spectral shape. Ruderman & Cheng (1988) have studied high-energy γ -ray pulsars and assigned short-period γ -ray pulsars into an evolution parth. As has been shown before, the critical parameters, the rotational energy-loss rate ($\dot{E}$), the spectral break point ($h\nu_c$), and the fraction of the rotational energy lost as synchrotron radiation ($L_{\text{synch}}/\dot{E}$) are estimated to be similar (within a factor of 2–3) for PSR 1509–58 and the Vela pulsar. We therefore expect their pulsed emissions to be similar both in spectrum and in normalized luminosity ($L_{\text{synch}}/\dot{E}$).

When observational results on PSR 1509–58 are compared with those of the Vela pulsar, PSR 1509–58 has very high efficiency of converting rotational energy loss to radiation in the X-ray/soft γ -ray band (Table 3) while the Vela pulsar is more efficient in the higher γ -ray band (Grenier et al. 1988). We note, in Figure 6, that the energy scale is shifted by ~ 2 decades between PSR 1509–58 and the Vela pulsar. The CHR outer gap model (Cheng et al. 1986a, b; Ruderman & Cheng 1988) as well as some other outer gap models (Arons 1990; Shibata

1991) make a generic prediction that the average energy of emitted photons moves higher as the conversion efficiency of the rotation-energy loss to radiation gets higher. The observational results on the Crab, Vela, and Geminga pulsars are regarded as in agreement with this prediction (Ruderman et al. 1993). Our observation and analysis summarized in Figure 6 clearly demonstrates that PSR 1509–58 is very different from the other three pulsars.

The observed broad single-peak pulse profile (Fig. 3) also appears different from the other pulsars and may be difficult to explain in the outer gap model. The phase spread of one pulse peak is generally predicted to be of the order of the beam spread or the angle of the fan beam (much less than 90°) in higher energy bands. Two peaks are generally expected. If we take the view that the pulse profile is determined primarily by the location of the emitting region (see for example Smith 1986), the observed profile seem to suggest PSR 1509–58 to be an aligned pulsar.

Another point to note in Table 3 is that the nonpulsed nebula component is small for PSR 1509–58 in the X-ray band. The smallness of the X-ray nebular luminosity has been explained by the difference in the rotational energy loss rate and the nebula size (Seward et al. 1984; Pacini & Salvati 1987; Seward & Wang 1988). In fact, PSR 1509–58 and the Crab pulsar look similar in spectrum, if we normalize the non-pulsed nebula flux by the rotational energy loss (Fig. 6).

Recently the polar cap model of X-ray/ γ -ray emission in rotation-powered pulsars has been extended to make some predictions on pulse profiles and emission spectra (Chiang & Romani 1992; Harding & Daugherty 1993). At present predictions are made only in a special geometry adjusted to reproduce the Crab and Vela pulse profile. A broad single peak will probably be predicted if the magnetic dipole is aligned with the rotation axis. The model predicts, however, a power-law spectrum similar to what the outer gap model predicts up to GeV range at which energies magnetic pair production begins to attenuate photons. Thus the observed spectra of PSR 1509–58 and the Vela pulsar are not explained in a uniform way.

6. CONCLUSIONS

We detected pulsed hard X-ray and soft γ -ray emission from PSR 1509–58 at the predicted period in a balloon observation in Brazil on 1991 November 19 (UT). The observed time profile of the pulsed emission shows a broad single peak (Figs. 2 and 3), similar to what has been observed in the X-ray band by *Ginga* (Fig. 2, Kawai et al. 1991). The pulsed flux in the energy band (47–710 keV) is consistent with the power-law spectrum with index $\alpha = 1.30 \pm 0.05$ determined in the X-ray band (Kawai et al. 1993) (Figs. 4 and 5). The total energy outflow in the X-ray/soft γ -ray band (2–710 keV) normalized by the rotational energy loss of PSR 1509–58 turns out to be an order of magnitude higher than that of the Crab pulsar and more than two orders of magnitude higher than that of the Vela pulsar (Table 3 and Figure 6).

The outer gap model by Cheng et al. (1986a, b) predicts PSR 1509–58 to have a similar emission spectrum as that of the Vela pulsar. Higher efficiency of converting the rotational energy loss to radiation, if compared with the Crab pulsar, is in general agreement with the CHR outer gap model. The observed emission spectrum (Figs. 4 and 5), however, is in sharp disagreement with that of the Vela pulsar and the predic-

tion of the model. The observed broad single-peak pulse profile (Figs. 2 and 3) may be accommodated, if the magnetic dipole is aligned with the rotational axis.

We believe predictions on the emission spectrum are similar in the CHR outer gap model and other pulsar models if the high-energy emission region is assumed to originate in the outer gap (Arons 1990). In fact, the model by Shibata (1991) in which the total X-ray/ γ -ray flux has been calculated based on the global structure of the pulsar magnetosphere, gives similar predictions.

Improvements on present pulsar models to explain the observed features of PSR 1509–58 are needed. So far, pulsar models have assumed the emission region to be confined either in the outer gap or over the polar cap. The emission spectrum is governed largely by the magnetic field strength and the electron mean free path of the emission region. In PSR 1509–58, X-ray and soft γ -ray emission region may be distributed over a wider region than in the Crab and Vela pulsars. Observations of this pulsar at higher energies and of the Vela and Geminga pulsars in the hard X-ray region will be important in clarifying the emission mechanism of the pulsar.

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