ASCA AND GINGA OBSERVATIONS OF GX 1+4

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ABSTRACT

The X-ray binary pulsar GX 1+4 was observed with Ginga every year from 1987 to 1991 and with ASCA in 1994. During the Ginga observations, GX 1+4 was in the steady spin-down phase, although the X-ray flux was not steady. Assuming a distance of 10 kpc, the absorption-corrected X-ray luminosity decreased down to \( L_{2-20\text{ keV}} = 2.7 \times 10^{36} \text{ ergs s}^{-1} \) in 1991, after the peak activity of \( L_{2-20\text{ keV}} = 1.2 \times 10^{37} \text{ ergs s}^{-1} \) in 1989. On the other hand, the absorption column density showed a drastic increase over the Ginga observation series. It was less than \( 10^{23} \text{ cm}^{-2} \) at the beginning of the series, and it reached a maximum of \( (1.4 \pm 0.2) \times 10^{24} \text{ cm}^{-2} \) in 1991, indicating a rapid accumulation of matter in the vicinity of the source. The center energy and equivalent width of the iron line were consistent with emission by isotropically distributed cold matter. The ASCA observation was performed on 1994 September 15, a month before the transition into a spin-up phase. The source brightened again to \( L_{2-20\text{ keV}} = 10^{37} \text{ ergs s}^{-1} \). The absorption column density was observed to decrease for the first time to \( (2.08 \pm 0.02) \times 10^{23} \text{ cm}^{-2} \). The ionization degree of iron in the absorbing matter was determined to be \( \text{Fe} \rightarrow \text{Fe} \text{IV} \) using the ratio of the line-center energy to the absorption-edge energy. The low ionization degree is consistent with an absorbing matter distribution extending \( \sim 10^{12} \text{ cm} \) from the source. We compared the results with optical observations and found that the optical data also supports the picture. Based on the geometrical model, possible causes of the bimodal behavior of the source are discussed.

Subject headings: binaries: symbiotic — pulsars: individual (GX 1+4) — X-rays: stars

1. INTRODUCTION

The X-ray pulsar GX 1+4 is the most enigmatic of all binary X-ray pulsars. It is identified with the symbiotic system V2116 Oph, which contains a magnetized neutron star accreting from the M6 III companion (Davidsen, Malina, & Bowyer 1977). GX 1+4 is a slow pulsar with a spin period of about 2 minutes. It has a hard energy spectrum and hence has been a good target for both soft and hard X-ray observations.

In the 1970s, GX 1+4 was a bright X-ray source with a typical 2–6 keV flux of 100 mcrab (McCintock & Leventhal 1989, and references therein). (Hereafter, the bandpass of flux measurement is 2–6 keV if not specified.) It showed the fastest spin-up among the binary X-ray pulsars with a mean rate of \( \dot{P}/P = -2.7 \times 10^{-2} \text{ yr}^{-1} \) (Elsner et al. 1985). In the early 1980s, the source entered into a low state. EXOSAT observations in 1983 failed to detect the source and set an upper limit of 0.5 mcrab (McCintock & Leventhal 1989, and references therein). Ginga detected GX 1+4 in 1987 at a flux level of 2 mcrab, and the source was found to be spinning down (Makishima et al. 1988). Subsequent Ginga and HEXE observations showed that the spin-down rate was remarkably constant at \( \dot{P}/P = 1.3 \times 10^{-2} \text{ yr}^{-1} \) in spite of a gradual increase by an order of magnitude in the X-ray flux (Sakao et al. 1990; Mony et al. 1991). The clear contrast of GX 1+4 in the 1970s and in the 1980s indicates the close connection between the high/low transition in luminosity and the spin reversal.

The spin-down rate was observed to decrease a little in 1990 and 1991, although subsequently a linear trend of spin-down was recovered with a slightly increased rate (Mandrou et al. 1994). A large flare in the hard X-ray band was detected by CGRO in 1993 September (Staubert et al. 1995), and the source brightened up to ~80 mcrab (40–100 keV) for a few weeks. A gradual increase of the spin-down rate had been observed for about 6 months before the flare (Finger et al. 1993), but the rate was constant during the flare at \( \dot{P}/P = 3.2 \times 10^{-2} \text{ yr}^{-1} \) (Staubert et al. 1995).

The spin period history of GX 1+4 has been almost continuously monitored by BATSE since 1991 (Chakrabarty et al. 1997). It revealed a short episode of spin-up in 1994 (Chakrabarty et al. 1994), which was accompanied by a large increase in the hard X-ray flux.

The 20–100 keV phase-averaged pulsed flux reached ~100 mcrab in 1994 November. The spin-up phase was terminated in 1995 March (Chakrabarty et al. 1995), and the spin-down resumed at a rate of \( \dot{P}/P = 4.8 \times 10^{-3} \text{ yr}^{-1} \).

The origin of this enigmatic behavior in GX 1+4 is not yet understood. Even the basic parameters of the system, such as the orbital period and the surface magnetic field of the neutron star, are not known. A binary period of 304 days was suggested by Cutler, Dennis, & Dolan (1986).
based on the fluctuation of the spin-up rate. However, optical monitoring of the H\textalpha\ emission line indicates that the period may be significantly greater than 304 days (Sood et al. 1995). If the spin behavior is analyzed in the framework of the accretion torque model by Ghosh & Lamb (1979a, 1979b) and Wang (1987), a very large magnetic field on the neutron star surface, $\sim 10^{14}$ G, is required (Makishima et al. 1988). Dotani et al. (1989) showed that even a moderate magnetic field of a few times $10^{12}$ G can explain the spin-down rate, if a retrograde accretion disk were formed around the neutron star. An energy-dependent pulse profile in hard X-rays is used to construct a model based on two-photon emission as the dominant continuum source in hard X-rays is used to construct a model based on two-photon emission as the dominant continuum source (Greenhill et al. 1993). The retrograde disk model is supported by the BATSE observations (Nelson et al. 1997), although some other possibilities such as the transition between Keplerian flow and advective flow in accretion geometry are also suggested (Yi, Wheeler, & Vishniac 1997).

In this paper, we report results obtained from the unpublished *Ginga* and new *ASCA* data.

2. OBSERVATIONS

The data that we analyzed in this paper were obtained with *Ginga* (Makino & The Astro-C Team 1987) and *ASCA* (Tanaka, Inoue, & Holt 1994). The main instrument on board *Ginga* is the Large Area Counter (LAC) (Turner et al. 1989), which consists of nonimaging, conventional proportional counters. The LAC has an effective area of 4000 cm$^2$ and covers an energy range of 1–37 or 2–60 keV depending on the high-voltage setting. It has the relatively poor energy resolution of $\sim 18\%$ at 6 keV. The field of view of the LAC is restricted by collimators to $1^\circ \times 2^\circ$ (FWHM).

*Ginga* observations of GX 1+4 were made on five occasions. The first three sets of data have already been analyzed, and the results have been previously published (Makishima et al. 1988; Dotani et al. 1989; Sakao et al. 1990). We used the fourth and fifth sets of data for the present analysis. The fourth set of observations was carried out on 1990 September 4–5 as a part of galactic ridge observations, and the fifth set was carried out on 1991 September 16. In the fifth observation, the high-voltage setting of the LAC was changed to cover 2–60 keV, while in the fourth observation, the nominal setting of 1–37 keV was adopted. Both sets of data were acquired in MPC1 mode with 48 energy channels. In this data mode, the temporal resolution was 0.5, 4, and 16 s for the high-, medium-, and low-bit rates, respectively. Unfortunately, most of the fifth observation was recorded in low-bit rate mode, and this limited the temporal resolution in later analysis.

*ASCA* carries four identical grazing-incidence X-ray telescopes (XRTs), and each XRT has an imaging spectrometer at its focal plane. The XRTs utilize nested thin-foil conical reflectors to achieve a large effective area (1200 cm$^2$ at 1 keV; Serlemitsos et al. 1995). A point-source image has a typical size of 3’ in half-power diameter. The focal plane detectors are two solid-state spectrometers (SISs) (Burke et al. 1994) and two gas imaging spectrometers (GISs) (Makishima et al. 1996). The SIS consists of four CCD chips optimized for X-ray photon detection. It covers an energy range of 0.5–10 keV, and a single chip covers a $11' \times 11'$ sky field. The SIS achieves high-energy resolution of 2\% (FWHM) at 6 keV. The GIS is a gas scintillation proportional counter with imaging capability. It covers an energy range of 0.7–10 keV and a field of view of 25' in radius. The GIS has an energy resolution of 7.8\% (FWHM) and a spatial resolution of 0.5 mm (FWHM), both at 6 keV.

*ASCA* observations of GX 1+4 were carried out on 1994 September 14–15. The observation mode of SIS was 1 CCD faint mode, and that of GIS was PH mode with standard bit assignment. Thus, the time resolution of SIS was 4 s, and that of GIS was 62.5 ms and 0.5 s for the high- and medium-bit rates, respectively. The journal of the observations is summarized in Table 1.

3. ANALYSIS AND RESULTS

3.1. Ginga Data

Raw data were first screened according to the good time intervals, which exclude South Atlantic Anomaly passages, Earth occultation of the source, and the periods of low cutoff rigidity (less than 6 GeV/c). Light curves of the data were then checked to remove parts of the data contaminated by particle events manually. These screened data were used for the subsequent analysis.

3.1.1. Timing Analysis

The pulse period of GX 1+4 was determined using an epoch-folding technique. We did not subtract background from the data because the timescale of the background variation was much longer than 10$^2$ s and did not affect the period determination of GX 1+4. The pulse period that gives the largest $\chi^2$ against a constant was searched. The time resolution of the data was 4 s in the 1990 observation, so we divided the folding pulse period into 28 phase bins. The time resolution was 16 s in the 1991 observation, and we divided the folding period into seven phase bins. Finer binnings were not appropriate because the pulse period is about 10$^3$ s. The heliocentric pulse periods that we obtained are listed in Table 2. Nondimensional average rates of pulse period change between the previous measurement and this measurement are also listed in Table 2. These results indicate that GX 1+4 was spinning down since 1987.

The folded light curves are shown in Figure 1. The pulse profile of the data set presented in Figure 1a is very similar to those in 1988 and 1989: double peaked in the low-energy band and single peaked in the high-energy band accompanied by a sharp and deep dip. The sharp dip observed in the data set in Figure 1a is not clear in the data set in Figure 1b. This may be due to the low time resolution of the data.

**TABLE 1**

| Data Set | Satellite | Start Time (UT) | End Time (UT) | Exposure (ks) | Energy Range (keV) |
|----------|-----------|----------------|--------------|--------------|-------------------|
| 1        | *Ginga*   | 1990 Sep 04 13:47 | 1990 Sep 05 04:28 | 10.8         | 1–37              |
| 2        | *Ginga*   | 1991 Sep 14 16:56 | 1991 Sep 16 01:41 | 37.8         | 2–60              |
| 3        | *ASCA*    | 1994 Sep 14 23:53 | 1994 Sep 15 22:00 | 30.0         | 0.5–10             |
TABLE 2

| Data Set | Mission | Epoch (MJD) | Pulse Period (s) | Period Derivative* (10^{-8}) |
|----------|---------|-------------|------------------|-------------------------------|
| 1        | Ginga  | 48,138.0    | 114.63 ± 0.02b   | 3.1 ± 0.1                     |
| 2        | Ginga  | 48,513.0    | 116.17 ± 0.03b   | 4.7 ± 0.2                     |
| 3        | ASCA   | 49,610.5    | 122.02 ± 0.03c   | 6.17 ± 0.03                   |

* Average between observations.

b Heliocentric value.

c Barycentric value.

3.1.2. Spectral Analysis

GX 1+4 is located close to the Galactic plane, so it is difficult to accurately estimate the contribution from the Galactic ridge emission (Koyama 1989, and references therein). For this estimation, we sampled the spectra at two points in the sky: \((l, b) = (3:215, 5:744)\) and \((5:795, 7:674)\); GX 1+4 \((1:943, 4:785)\) is located on the line connecting these two points. The data were obtained as a part of Galactic ridge observations, in which the data of GX 1+4 were also acquired. These two points are well separated from nearby bright sources such as the Kepler supernova remnant and GX 9+9, and hence the spectra can be regarded as those of the pure Galactic ridge emission. The spectra were fitted by a model of thermal bremsstrahlung and a Gaussian line with a center energy of 6.7 keV—the energy of Fe XXV Kα. The temperature of the thermal bremsstrahlung was found to be 4.78 and 2.14 keV, respectively, and the flux in units of count rate at spectral peak was 2.5 ± 0.7 and 0.95 counts s^{-1} keV^{-1}, respectively. The Gaussian line was 0.89 ± 0.31 counts s^{-1} at the former position and not detected at the latter. The flux of the Galactic ridge emission at the position of GX 1+4 was then estimated by linear interpolation of the best-fit parameters. The resultant temperature and spectral peak flux were 6.1 keV and 3.27 counts s^{-1} keV^{-1}, which corresponds to 1–37 keV flux of 18.1 counts s^{-1}. The iron-line flux was estimated to be 1.2 counts s^{-1}. The ridge emission thus determined was subtracted from the energy spectra of GX 1+4 together with the intrinsic and cosmic X-ray background utilizing the method described in Hayashida et al. (1989). The resultant, background-subtracted spectra are shown in Figure 2.

The energy spectrum of the observation in 1991 was well fitted by a power law attenuated by a cold absorber, as was the case in the three previous observations in 1987, 1988, and 1989. The spectrum of 1990 was, however, better expressed by a partial covering model of a power-law continuum. A prominent iron line was also detected at about 6.4 keV. This line is considered to be a fluorescence line of neutral or slightly ionized iron in the vicinity of the source, not a collisionally excited emission line of highly ionized iron whose center energy is at 6.7 or 6.9 keV. The fluorescence line provides important information on the physics of the system (Makishima 1986). The center energy gives the ionization stage of the illuminated matter and thus the distance of the plasma from the source and the density. The geometry of the attenuating matter can be derived from the equivalent width of the line and the attenuation column density. Therefore, it is essential to resolve a 6.4 keV line from 6.7 and 6.9 keV lines and determine the central energy and equivalent width precisely. Unfortunately, the 1991 energy spectrum has coarse energy binning and the line-center energy could not be determined with enough accuracy to distinguish the 6.4 and 6.7 keV lines. As seen later, ASCA data show that the iron line in GX 1+4 is centered at 6.4 keV. Thus, in the subsequent analysis of Ginga spectra, we fixed the line-center energy to 6.4 keV. We summarize in Table 3 the best-fit parameters of both sets of observations. The spectra and the best-fit model are shown.

![Figure 1](image-url)

**Fig. 1.**—Folded light curves of the Ginga data in (a) 1990 September (1–37 keV) and (b) 1991 September (2–60 keV). Background and Galactic ridge components were not subtracted. See Table 2 for the heliocentric pulse period of these data.
in Figure 2. We detected significant X-ray emission from GX 1+4 up to \( \sim 50 \) keV in data set 2. However, we could not find any significant structure of cyclotron resonant scattering in the energy spectrum.

The absorption-corrected X-ray luminosity is calculated as \( L_{2-20\,\text{keV}} = 0.72 \times 10^{37} \) and \( 0.27 \times 10^{37} \text{ ergs s}^{-1} \) for 1990 and 1991, respectively, for the assumed distance of 10 kpc. In 1989, the source was found to be as luminous as \( 10^{37} \) ergs s\(^{-1}\). It was interpreted that GX 1+4 was recovering from the low state (Sakao et al. 1990). In 1991, however, it decreased again to the very faint level as in 1987 and was still in the steady spin-down phase.

### 3.2. ASCA Data

GX 1+4 was detected with both GIS and SIS with an average count rate of about 1 count s\(^{-1}\) (GIS: 1–10 keV). No significant time variation was seen except for the 122 s pulsation. Source photons were extracted from the circular region centered on the GIS image peak with a radius of 6@. As for SIS, photons from the whole chips (S0C1 and S1C3) were used to get better statistics. Both timing and spectral analyses were done using these source photons.

#### 3.2.1. Timing Analysis

The pulse period of GX 1+4 was determined using the GIS data, which have superior time resolution. We applied neither detector-background subtraction nor dead-time correction to the data because such corrections are not significant for timing analysis of medium-brightness sources such as GX 1+4. Using the epoch-folding technique, we found the barycentric pulse period to be 122.019 \( \pm 0.027 \) s. Folded pulse profiles are shown in Figure 3 in several different energy bands. Deep dips similar to that observed with *Ginga* are clearly seen in the pulse profile. Below 3 keV, Galactic ridge emission dominates and hence the pulse amplitude is much reduced. It should be noted that the dip structure in the pulse profile becomes shallow in the energy band between 6.28 and 6.52 keV, where the fluorescent iron line is dominant (see Fig. 4). Iron-line flux contributes about 40% in this energy band, and the reduction of the dip depth \( (\sim 50\% \text{ in } 6.28–6.52 \text{ keV compared to } \sim 80\% \text{ in the other bands}) \) is consistent with no pulsation in the iron emission line. This conforms to the scenario that the fluorescent iron line originates from the spherically symmetric absorbing matter, as discussed in § 4. The other energy bands besides less than 3 keV and 6.28–6.52 keV show a similar pulse profile and pulse fraction, indicating no pulse phase dependence of the spectral parameters, such as the photon index or the absorption column density.

#### 3.2.2. Spectral Analysis

We calculated phase-averaged energy spectra of SIS and GIS using the source photons described previously. For

### TABLE 3

Spectral Parameters of GX 1+4

| DATA SET | Normalization\(^a\) | Photon Index | \(N_H\)^10\(^{22}\) cm\(^{-2}\) | EW (keV) | Center (keV) |
|----------|---------------------|--------------|-----------------|--------|-------------|
| 1......... | 0.156 \(\pm 0.026\) | 1.98 \(\pm 0.07\) | 3.0 \(\pm 0.3 (A^b = 0.87)\) | 0.11 \(\pm 0.03\) | 6.4 (fixed) |
| 2......... | 0.022 \(\pm 0.015\) | 1.49 \(\pm 0.23\) | 14 \(\pm 2\) | 3.1 \(\pm 0.2\) | 6.4 (fixed) |
| 3......... | 0.050 \(\pm 0.002^c\) | 1.19 \(\pm 0.09^c\) | 2.15 \(\pm 0.03^c\) | 0.094 \(\pm 0.005^c\) | 6.42 \(\pm 0.04^d\) |

\(^a\) In units of photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) at 1 keV.

\(^b\) Partial covering factor.

\(^c\) Average between SIS and GIS.

\(^d\) SIS only. Including systematic errors.
the GIS spectrum, background photons were extracted using the GIS data from the region symmetric to the source region relative to the bore sight axis of the XRT. These background data include Galactic ridge emission. We constructed an energy spectrum of the Galactic ridge emission by subtracting the high-latitude background data, which are publicly available. We found that the background spectrum can be well represented by emission from an optically thin hot plasma model by Mewe, Gronenschild, & van den Oord (1985). The best-fit temperature obtained was 6.1 keV with an equivalent hydrogen column density of $2.3 \times 10^{21}$ cm$^{-2}$. Because we could not extract background data for SIS due to the small field of view, we just subtracted the high-latitude blank sky data as background. Galactic ridge emission was included in a model spectrum for spectral fitting.

![Fig. 3](image3.png)

**Fig. 3.**—Folded light curves of the SIS data in six energy bands in 1994 September. The temporal average of the flux of each curve is normalized to unity. Both sensors are combined. The epoch at phase 0 is 49,610.00 (MJD). Background and Galactic ridge components were not subtracted.

![Fig. 4](image4.png)

**Fig. 4.**—Spectra taken with *ASCA* (a) SIS and (b) GIS. The best-fit model is plotted as a histogram. See Table 3 for the best-fit parameters. From the GIS data, the Galactic ridge emission is subtracted, while only the diffuse cosmic X-ray background component is subtracted from the SIS data.
We found that a single power law modified by cold matter absorption plus a narrow emission line can reproduce the energy spectrum. The model functions we employed are

\[
\begin{align*}
\ell_{\text{SIS}}(E) &= f_{\text{Mewe}}(E, T) \exp\left(-\sigma_{\text{HI}} N_{\text{H}}\right) \\
&+ \left\{ \frac{A E^{-\Gamma}}{\text{width}} + B \exp\left[-\left(\frac{E - E_c}{E_{\text{width}}}\right)^2\right] \right\} \exp\left(-\sigma_{\text{HI}} N_{\text{H}}\right) \\
\ell_{\text{GIS}}(E) &= \left\{ \frac{A E^{-\Gamma}}{\text{width}} + B \exp\left[-\left(\frac{E - E_c}{E_{\text{width}}}\right)^2\right] \right\} \exp\left(-\sigma_{\text{HI}} N_{\text{H}}\right)
\end{align*}
\]

for the SIS and the GIS data, respectively. Here, \( E \) is the X-ray energy, \( f_{\text{Mewe}}(E, T) \) is the model spectrum by Mewe et al. (1985), \( \Gamma \) is the photon index, \( \sigma \) is the photoabsorption cross section, \( N_{\text{H}} \) is the hydrogen equivalent column density, \( E_c \) is the line-center energy, \( E_{\text{width}} \) is the intrinsic line width, which is assumed to be effectively zero in the fitting, and \( A \) and \( B \) are flux normalization factors. The model of the Galactic ridge emission \( f_{\text{Mewe}}(E, T) \) is included only in the SIS because it is subtracted from the GIS spectrum. The spectra and the best-fit model are shown in Figure 4, and the best-fit parameters are listed in Table 3. The luminosity of GX 1 + 4 in 2–20 keV (same as the Ginga band) is estimated as \( 1.1 \times 10^{37} \) ergs s\(^{-1}\) using the best-fit model for the assumed distance of 10 kpc.

To determine the ionization (state) of iron, we fitted the 5–10 keV SIS data with a power law attenuated by the iron K edge plus iron K \( \alpha \) and K \( \beta \) lines. The line-flux ratio of the iron K \( \beta \) to K \( \alpha \) was fixed to the value expected in fluorescence of Fe I. The center-energy ratio of the K \( \beta \) to K \( \alpha \) was also fixed to the value expected in Fe I. We tested several values of this ratio and found that they do not change the result. For SIS0 and SIS1, the center-energy of the iron K \( \alpha \) line was fitted to be \( 6.400_{-0.012}^{+0.012} \) and \( 6.440_{-0.012}^{+0.012} \) keV, respectively, and the energy of the iron K edge was fitted to be \( 7.163_{-0.072}^{+0.072} \) and \( 7.216_{-0.072}^{+0.072} \) keV, respectively. The errors are 90% confidence intervals. The line-center energies of both sensors were inconsistent with each other. This is considered to be due to gain-calibration uncertainties of the SIS caused by the decreasing charge transfer efficiency (e.g., Gendreau 1995; Yamashita et al. 1997). For measurement of the ionization degree free from the gain uncertainties, we utilize the ratio of the edge energy to the line-center energy. The ratios were \( 1.119_{-0.011}^{+0.011} \) and \( 1.120_{-0.011}^{+0.011} \) for SIS0 and SIS1, respectively. It should be noted that these values are consistent with each other within the statistical errors. Thus, the averaged energy ratio was accurately determined to be \( 1.120_{-0.008}^{+0.008} \), which corresponds to Fe I–Fe IV (Lotz 1968).

3.2.3. Image Analysis

We searched for a dust-scattering halo around GX 1 + 4. X-rays from a source near the Galactic plane such as GX 1 + 4 would suffer from scattering by interstellar matter and may produce a halo around the source. Efficiency of the dust scattering is a strong function of X-ray energy, and the dust-scattering halo is most prominent at lower energies. To search for the halo, we compared the radial profile of the image above and below 5 keV. The dividing energy was selected to be as low as possible while retaining statistical significance in the lower energy band. This method is unaffected by possible attitude fluctuation of the satellite during the observations. Although GX 1 + 4 is located very close to the direction of the Galactic center, the effect of dust scattering was not seen in the image. This is not surprising because the source is heavily absorbed and has little X-ray emission in the lower energy band, where the dust scattering is most prominent. Predehl, Friedrich, & Stauber (1995) found an X-ray halo around GX 1 + 4 in a ROSAT PSPC image below 2.4 keV. The halo extended to a few arcminutes and was brighter than GX 1 + 4. Predehl et al. suggested that this halo was the reflection of the flare 70 hr before the ROSAT observation. That is consistent with our result.

4. DISCUSSION

Through the Ginga and ASCA observations, we found large changes in the energy spectrum, especially for the absorption column density and the iron emission line. On the other hand, the spin-down rate decreased slightly in 1990 and 1991 followed by an increased rate, and GX 1 + 4 entered a short episode of spin-up in 1994 just after the ASCA observation. The spin-up episode is recognized as a glitch in 1995 in Figure 1 of Chakrabarty et al. (1997) or a flare beginning at MJD 49,638 in Figure 2 of the same paper. In this section, we consider the connection between the circumstellar matter and the spin period change.

4.1. Geometry of the Circumstellar Matter

Hydrogen column densities obtained from the GX 1 + 4 observations with Ginga and ASCA range between \( 10^{23} \) and \( 10^{24} \) cm\(^{-2}\). These column densities are several orders of magnitude larger than the Galactic absorption of \( 6 \times 10^{21} \) cm\(^{-2}\) (Dickey & Lockman 1990) and are considered to have a circumstellar origin. The equivalent width of the fluorescent iron line is useful to deduce the distribution of the circumstellar matter. We show in Figure 5 a scatter plot of the equivalent width of the iron line and the hydrogen column density obtained from the ASCA and all of the
Ginga observations. The relation expected from a spherical distribution of matter is also indicated in the figure. The column density drastically increased to $10^{24} \text{cm}^{-2}$ in 1991 with the increase of iron equivalent width to 3 keV. This equivalent width is very close to that expected from a spherical distribution of the matter. The ASCA observation showed that the column decreased in 1994 to a level comparable to that in 1990. When the column density is relatively low, the data points are scattered around the relation expected from the spherical distribution, but the deviation is at most factors of a few. This scatter may be due to a clumpy structure of the circumstellar matter. In fact, we found that a partial covering model gives a better fit to the energy spectrum in 1990. This supports the assumption that the circumstellar matter has a clumpy distribution. Except for this clumpiness, we can consider the circumstellar matter to have a spherical symmetric distribution around GX 1+4.

We found from the ASCA observation that the ionization degree of iron in the circumstellar matter is very low (Fe I–Fe IV). Thus, the $\xi$-parameter ($= L_X/N_P$), which determines the photoionization degree, may be smaller than 30 ergs cm s$^{-1}$. With the knowledge of $L_X$ and $N_P$, we can estimate the characteristic scale of the attenuating matter distribution or the typical distance of the matter from the source. ASCA data are not very useful for evaluating $L_X$ because the data cover only below 10 keV. According to balloon experiments, the hard X-ray luminosity (20–100 keV) was $\sim 2 \times 10^{37}$ ergs s$^{-1}$ (for the distance of 10 kpc) during the 1990s, except for the bright state in 1993 December (Rao et al. 1994; Paul et al. 1997). Therefore, we assume $L_X = 2 \times 10^{37}$ ergs s$^{-1}$ as the total X-ray luminosity during the ASCA observation. This X-ray luminosity and the column density of $N_H = 2.2 \times 10^{23}$ cm$^{-2}$ give the radius of the attenuating circumstellar matter to be larger than $3 \times 10^{12}$ cm. Thus, it is concluded that the source was enveloped in a spherical gas cloud with a radius of greater than $3 \times 10^{12}$ cm. Considering various uncertainties in the above calculation, the result should be regarded as an order-of-magnitude estimation. However, it is still larger than the corotation radius $r_{co} = 4 \times 10^{10}$ cm and the Alfven radius $r_A = 4 \times 10^{10}$ cm, even for the extraordinarily strong magnetic field of $10^{14}$ G. Instead, it may be comparable to the size of the Roche lobe, if the binary period is of order 1 yr.

### 4.2. X-Ray Heating of the Circumstellar Matter

GX 1+4 is thought to accrete matter from the slow stellar wind of the companion. The large size of the circumstellar matter and its nearly spherical distribution around GX 1+4 is naturally interpreted as the dense stellar wind from the companion captured in the Roche lobe of GX 1+4. The temperature of the plasma is estimated to be a few electron volts from the value of the $\xi$-parameter ($\sim 30$ ergs s$^{-1}$ cm), which corresponds to a thermal velocity of about 30 km s$^{-1}$. On the other hand, the Kepler velocity at $10^{12}$ cm from the neutron star is about 100 km s$^{-1}$. Thus, the circumstellar matter is considered to be bound to GX 1+4. It is noteworthy that, if GX 1+4 becomes slightly brighter, the circumstellar matter can easily escape from GX 1+4. Suppose GX 1+4 becomes 3 times more luminous; the $\xi$-parameter of the circumstellar matter would increase up to $10^2$. This corresponds to a plasma temperature of $\sim 30$ eV and hence a thermal velocity of 100 km s$^{-1}$. This is comparable to the Keplerian velocity, and the plasma can escape from GX 1+4.

During the spin-down phase of GX 1+4 since 1985, the stellar wind captured by GX 1+4 may be stagnated around the neutron star at a distance of $10^{12}$ cm or more. The low-luminosity characteristic of the spin-down phase would reduce the amount of matter escaping from GX 1+4 by X-ray heating, resulting in a larger column density. Some other effects such as a change of the wind velocity may also have contributed to the increase in column density. Because the amount of the stellar wind captured by the neutron star depends on the wind velocity as $\propto v_w^4$, a small change of the wind velocity can result in the large change of the captured mass.

When GX 1+4 spins up, as in the 1970s and in the short episode of 1994–1995, the X-ray luminosity is at least several times larger than that in the spin-down phase. The X-ray luminosity may be large enough to heat up the circumstellar matter and to expel much of it from the vicinity of GX 1+4. This explains the relatively low column density observed during the 1970s (Becker et al. 1976).

Just before the short episode of spin-up in 1994–1995, the column density was observed with ASCA to be reduced to the level of 1990. This means that most of the accumulated circumstellar matter had been expelled from the vicinity of GX 1+4 before the transition to spin-up. Thus, it is suspected that the accumulation of the circumstellar matter may not be the cause of the spin-up and is just controlled by the X-ray luminosity. This may be understood if the matter that affects the spin period change is located near the Alfven radius, not at the distance of $10^{12}$ cm from the neutron star.

### 4.3. Optical Observations

Optical observation is powerful for plasma diagnosis, and it is important to check whether our interpretation of the X-ray data is consistent with optical data or not. Here we briefly describe a preliminary analysis of optical observations and examine the consistency between the two bands. We do not discuss this in detail, since it will be reported in a forthcoming paper by Greenhill (1998).

V2116 Oph, the optical counterpart of GX 1+4, was observed with the 3.9 m Anglo-Australian Telescope (AAT) and the RGO spectrograph on 1994 September 25, 11 days after the ASCA observations. The measurements covered the wavelength range 3700–8900 Å with a resolution of 3.2 Å. On September 26, measurements centered on the Hα bands were made with the Mount John University Observatory 1 m telescope on five nights (August 25 and 27, September 2, and October 3 and 5) covering the time of the ASCA observations. The Hα flux increased slowly during this period and was about 0.4 mag brighter on October 5. The $V–I$ color changed only marginally. In view of these relatively small changes, we believe that our AAT data are representative of conditions in the source during the ASCA observations.

The measured and dereddened fluxes of some prominent emission lines are listed in Table 4. The reddening correction assumes the same interstellar extinction as observed by Chakrabarty & Roche (1997). The observed Hα flux (1.6 $\times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) was about half the value observed by Davidsen et al. (1977) during the high state in the mid-1970s and by Chakrabarty & Roche (1997) in 1993.
The measured Hα/Hβ line strength ratio of \(~30\) was less than 25% of the ratio measured by Davidsen et al. during the high state. Numerous Balmer, Paschen, He I, O I, O II, [O III], Na I, Ca II, and Fe II lines were seen in emission, but higher excitation lines were weak or undetected. He II \(\lambda 4686\) was weak, and the C II/N III feature common in X-ray sources at 4640–4650 Å was not detected; nor was the 6830 Å Raman line, although this was very strong during the high state and in 1988 (Davidsen et al. 1977; Chakrabarty & Roche 1997). The O I \(\lambda 8446\) line, an indicator of Hα optical depth (Netzer & Penston 1976), was almost an order of magnitude fainter relative to Hα than during the 1993 measurements by Chakrabarty & Roche (1997).

Following Chakrabarty & Roche (1997), we assume that the emission lines are excited by photoelectric interactions in circumstellar matter by UV emission from the disk. Further, we adopt the hypothesis developed earlier that the matter is trapped in the gravitational field of the neutron star. The Hα line width (\(~2\) Å FWHM after correction for the spectrograph resolution) is consistent with Doppler broadening due to matter gravitationally bound to the neutron star at a radius of \(\sim 3 \times 10^{13}\) cm. As noted by Chakrabarty & Roche (1997), the presence of Fe II and absence of Fe III lines implies a temperature in the emission region of less than 30,000 K. The ratio of the corrected O I \(\lambda 8446\) to Hα emission is \(~0.01\), indicating an Hα optical depth \(~150\) (Netzer & Penston 1976). From this and the corrected line strength ratios of the first four Balmer lines we find, using the model of Drake & Ulrich (1980), an electron density \(n_e \sim 3 \times 10^{10}–10^{11}\) cm\(^{-3}\) and a temperature \(~20,000\) K in the emission-line region. Similar values for the electron density and plasma temperature are obtained from the ratios of the He I \(\lambda\lambda 5876, 6678\) and 7065) emission lines (Proga, Mikolajewska, & Kenyon 1994). These values are consistent with the hydrogen equivalent column density \(N_H = 2 \times 10^{23}\) cm\(^{-2}\) and plasma temperature derived from the ASCA spectroscopy assuming a spherical distribution of matter with a radius of \(\sim 3 \times 10^{12}\) cm about the source.

The densities are 1–2 orders of magnitude greater than those estimated by Davidsen et al. (1977) and by Chakrabarty & Roche (1997), and the radius is an order of magnitude smaller. Thus it is shown that the parameters of the system derived from the X-ray data, assuming a spherical distribution of circumstellar matter, coincide with those of the optically emitting plasma.

Since the separation of the neutron star and its giant companion is expected to be greater than 1 AU \(\sim 10^{13}\) cm), the matter in our model can be bound to the neutron star. Clearly, in the Davidsen et al. (1977) model, the emission region surrounds the whole binary system.

### 4.4. A Negative Feedback Mechanism

The Ginga and ASCA observations suggest that gas is accumulated in the vicinity of the source, probably by the stellar wind from the companion star, and may be blown off by an increase in X-ray luminosity. If the accreting matter is supplied from the stellar wind as suggested (e.g., Dotani et al. 1989; Davidsen et al. 1977), even a small increase in X-ray luminosity would lead to a decrease in accretion. This constitutes a negative feedback process and suppresses the X-ray luminosity. The situation is similar to the self-regulation of the luminosity at the Eddington limit. GX 1 + 4 entered a low state in the early 1980s, and, except for occasional short flares (Chakrabarty et al. 1997), remained faint until the ASCA observation in 1994. During the spin-down phase, the activity may be suppressed to a low level by the negative feedback mechanism. The condition for the mechanism to work is rather difficult to satisfy compared to Eddington accretion: (1) The \(\xi\)-parameter of the accretion flow needs to be high enough so that the thermal velocity can exceed the escape velocity. In the case of GX 1 + 4, the relatively low density of the accumulated matter, \(\sim 10^{11}\) cm\(^{-3}\) in 1991, resulted in a large \(\xi\)-parameter. On the other hand, in binaries in which the accretion matter is supplied by Roche lobe overflow, the density, \(\sim 10^{16}\) cm\(^{-3}\), is presumably too high for the mechanism to work. (2) The flow velocity must be lower than the thermal velocity attainable through X-ray heating. If the ram pressure of the flow is higher than the thermal pressure, trapped matter will not be blown off by X-ray heating. The typical wind velocity of M giants is \(10–30\) km s\(^{-1}\), and it is comparable or smaller than the thermal velocity of a plasma of \(\xi \sim 30\). When GX 1 + 4 is in a flare state and \(\xi \geq 100\), the thermal velocity exceeds the wind velocity. In the case of massive binaries with early-type companion stars such as Cen X-3 or Vela X-1, the wind is supersonic and the negative feedback mechanism is not likely to work, even if the sources are wind fed.

Chakrabarty, van Kerkwijk, & Larkin (1998) reported that the wind velocity of GX 1 + 4 is as large as \(250 \pm 50\) km s\(^{-1}\). Chakrabarty et al. suggested that radiation from the accretion disk or the neutron star may contribute to the acceleration of the outflow. That is consistent with the picture of the negative feedback, which predicts an outflow...
of circumstellar matter heated by the source. However, if the initial velocity of the stellar wind were as large as 250 km s$^{-1}$, our model would fail.

It should be noted that this negative feedback will not keep the X-ray luminosity constant. The X-ray source blows off only matter located far from the source with small gravitational binding energy. Therefore, the fuel supply decreases after a certain time comparable to the orbital period. Assuming the central mass to be 1.4 $M_{\odot}$, the orbital period is estimated to be $10^5$ days at the distance of $10^{12}$ cm. Such a negative feedback with a time delay would result in temporal variability such as oscillations or limit cycles. This mechanism predicts that large X-ray flares cannot last long because they even blow off matter close to the source and that small flares or weak activities last longer. That is qualitatively consistent with the pulsed flux history reported by Chakrabarty et al. (1997).

4.5. Spin-down and Spin-up Phase

Our interpretation of the variability in the luminosity and the absorbing column density through the negative feedback mechanism explains the very steady spin-down trend. The mass supply, averaged over a time longer than the feedback timescale, would not change very much even if the mass-loss rate of the companion changes considerably. Either the retrograde disk or propeller effect processes can spin-down the neutron star steadily under the feedback mechanism.

In the spin-up phase during the 1970s and in 1994, the feedback mechanism obviously did not work. In the 1970s, the luminosity was typically as high as $10^{37} - 10^{38}$ erg s$^{-1}$ and was enough to blow off a stellar wind with a velocity of 10 km s$^{-1}$ and a density of less than $10^{11}$ cm$^{-3}$. The wind could not reach the surface of the neutron star unless it was more dense than $10^{14}$ cm$^{-3}$. To avoid blowoff, the accreting matter had to be supplied by a very dense stellar wind or by a Roche lobe overflow. The condition of transition between spin-down and spin-up phases is not understood yet. Since the companion is a low-mass star, X-ray irradiation of the surface may affect the thermal structure and the evolution (e.g., Podsidiakovski 1991; D’Antona & Ergma 1993). Harpaz & Rappaport (1994) show that such a star may repeat short episodes ($1-100$ yr) of mass transfer. It is possible that the spin-up and spin-down phases of GX 1 + 4 are part of the episodic mass transfers induced by X-ray irradiation.

5. CONCLUSION

GX 1 + 4 in spin-down phase was observed with Ginga in 1990 and 1991 and with $ASCA$ in 1994, a month before the transition to a short spin-up episode. The behavior of the source in 1990 and 1991 can be summarized as follows.

1. It was found that the absorption column density drastically increased to $N_H = (1.4 \pm 0.2) \times 10^{24}$ cm$^{-2}$ in 1991, indicating a rapid accumulation of matter in the vicinity of the source.
2. The luminosity decreased to $L_{2-20 \text{ keV}} = 0.72 \times 10^{37}$ ergs s$^{-1}$ in 1990 and to $0.27 \times 10^{37}$ ergs s$^{-1}$ in 1991, which is almost the same level as the lowest activity in 1987. Nevertheless, the spin-down rate was very stable at $(3-4) \times 10^{-8}$ during the time.

Properties of the source deduced from the $ASCA$ observation can be summarized as follows:

1. The absorption column density decreased to $N_H = (2.08 \pm 0.02) \times 10^{24}$ cm$^{-2}$ in 1994 after a long interval in a high-absorption phase.
2. The ionization stage of iron in the absorbing matter was derived to be Fe I – Fe IV from the ratio of the absorption-edge energy to the emission-line energy.
3. The $\xi$-parameter of the absorbing matter was $\lesssim 30$, consistent with a spherical distribution with a radius of greater than $3 \times 10^{13}$ cm about the source.
4. The luminosity brightened to $L_{2-20 \text{ keV}} = 1.1 \times 10^{37}$ ergs s$^{-1}$, which is the brightest in the spin-down phase and almost comparable to that in the highly active spin-up phase.

The picture of GX 1 + 4 in a gas cloud is also supported by the optical observations covering the $ASCA$ observation. The Doppler broadening of the H$\alpha$ line was consistent with the Kepler motion at $\sim 3 \times 10^{12}$ cm from a neutron star, and the electron density and temperature estimated from the line strength ratios were consistent with the values expected from the picture.

To explain the accumulation and the disappearance of the absorbing matter, a negative feedback mechanism stabilizing the spin-down rate is suggested. Gas supplied by a slow stellar wind from the companion star would be blown off if the luminosity of the neutron star is high. When the luminosity is low, the neutron star would accrete and increase the luminosity. Therefore, the accretion rate and thus the spin-down rate may be stabilized under a certain level. This mechanism does not depend on the nature of the unknown spin-down mechanism, for which a retrograde disk and high magnetic field were proposed.

Since this negative feedback mechanism will not explain transitions between spin-up and spin-down, the transitions should be explained by some other mechanism such as episodic mass transfers.

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