THE EMISSION OF CYGNUS X-1: OBSERVATIONS WITH INTEGRAL SPI FROM 20 keV TO 2 MeV

E. JOURDAIN1,2, J. P. ROQUES1,2, AND J. MALZAC1,2
1 Université de Toulouse, UPS-OMP, IRAP, Toulouse, France
2 CNRS, IRAP, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France

Received 2011 August 2; accepted 2011 September 8; published 2011 December 14

ABSTRACT

We report on Cyg X-1 observations performed by the SPI telescope on board the INTEGRAL mission and distributed over more than 6 years. We investigate the variability of the intensity and spectral shape of this peculiar source in the hard X-ray domain, and more particularly up to the MeV region. We first study the total averaged spectrum which presents the best signal-to-noise ratio (4 Ms of data). Then, we refine our results by building mean spectra by periods and gathering those of similar hardness. Several spectral shapes are observed with important changes in the curvature between 20 and 200 keV, even at the same luminosity level. In all cases, the emission decreases sharply above 700 keV, with flux values above 1 MeV (or upper limits) well below the recently reported polarized flux, while compatible with the MeV emission detected some years ago by the Compton Gamma-ray Observatory/COMPTEL. Finally, we take advantage of the spectroscopic capability of the instrument to seek for spectral features in the 500 keV region with negative results for any significant annihilation emission on 2 ks and day timescales, as well as in the total data set.

Key words: methods: observational – radiation mechanisms: general – X-rays: binaries – X-rays: individual (Cyg X-1)

Online-only material: color figures

1. INTRODUCTION

Cyg X-1 is an unavoidable target for any high-energy instrument. Being one of the most luminous sources (up to the MeV range), it represents an ideal lab to study the mechanism at work in the direct environment of a black hole. There, the accretion flow is thought to form an optically thick disk and/or an optically thin corona, while the observed radio jets could originate from the same area (see, e.g., the review by Done et al. 2007). The high-energy radiation provides insights on the physical processes at work in this region. Thanks to its persistent high flux (∼1 crab) and usually hard spectrum, Cygnus X-1 is easy to observe and there are numerous measurements of its spectrum and variability in X-rays. At higher energies, however, the results are very scarce. Very few instruments were able to explore the properties of the emission above 200 keV.

The high-energy emission of Cyg X-1 is relatively well known from soft X-rays up to a few hundred keV. The shape of the spectrum is variable and can change dramatically on timescales as short as a day. There are however two main, relatively stable, spectral states: the Hard State (HS, corona dominated) and the Soft State (SS, disk dominated). Their description can be found in various papers (see, for example, Liang & Nolan 2018; Gierlinski et al. 1997, 1999). So far, the MeV region of the spectrum was best explored by the Compton Gamma-ray Observatory (CGRO). McConnell et al. (2002) have shown that, even though the HS hard X-ray emission is dominated by a thermal Comptonization component, both HS and SS spectra present a non-thermal power-law component extending above 1 MeV with a slope of 2.6 in the SS and $\Gamma \gtrsim 3$ in the HS. Moreover, broad features around 1 MeV have been observed on several occasions in the past (see, for example, Bassani et al. 1989 and references therein).

Since the CGRO observatory, however, only the INTEGRAL mission contains an instrument exploring the same energy domain. Recently, Laurent et al. (2011) stacked all the INTEGRAL/IBIS (Imager on Board INTEGRAL) data available for Cygnus X-1 and detected the presence of a non-thermal power-law component between 400 keV and 2 MeV. Interestingly they found that, contrary to the thermal Comptonization component present below 400 keV, the non-thermal power-law emission appears to be strongly polarized. This non-thermal component appears to have a flux that is stronger than that measured by CGRO by a factor 5–10 and a much harder spectral slope $\Gamma \simeq 1.6$. Here, we use another INTEGRAL instrument operating in this energy range, the spectrometer SPI, to investigate the high-energy spectral shape of Cyg X-1 and test the presence of non-thermal high-energy excess.

Our first goal is to take advantage of the sensitivity achieved with the SPI detector and the large amount of data and perform a detailed analysis of the energy extent of the hard X-ray emission together with its spectral variability.

Moreover, the spectroscopic capability of the germanium crystals allows us to seek for the presence of spectral features linked to the annihilation process.

Hereafter, we present briefly the instrument, data set, and the method followed for the analysis. Then, we report on our results and start by examining the total mean spectrum to determine the emission above a few hundred keV, where scarcity of photons requires the exposure to be as long as possible. In a second step, we analyze the source behavior during individual revolutions and build several averaged spectra, following some hardness criteria which can be considered as characteristic of the spectral state of the source. We conclude with a comparison with previous results.

* Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Spain, and Switzerland), Czech Republic and Poland with participation of Russia and USA.
2. INSTRUMENT, OBSERVATIONS, AND DATA ANALYSIS

SPI is a spectrometer on board the *INTEGRAL* observatory operating between 20 keV and 8 MeV. The description of the instrument and its performance can be found in Vedrenne et al. (2003) and Roques et al. (2003). The main features of interest for our study are a large field of view (FoV) (30°) with an angular resolution of 2/6 (FWHM) based on a coded aperture mask. The germanium camera, beyond an excellent spectroscopic capability, offers a good sensitivity over more than two decades in energy with a unique instrument. It is surrounded by a 5 cm thick BGO shield (ACS, anti-coincidence shield) which measures the particle flux. This latter can be used as a good tracer of the background level.

During a 3 day orbit, the usual dithering strategy (Jensen et al. 2003) consists of a hundred 30–40 minute exposures (also called scw for “science window”) with a given region scanned in 2° steps following pre-determined patterns. The recommended pattern for SPI observations is a grid of 5 × 5 around the chosen target. Unfortunately, in order to satisfy more proposers, with a few exceptions, most of the Cyg X-1 data have been obtained through “amalgamated” observations, i.e., with the pattern center somewhere between Cyg X-1 and the Cyg A region. As a consequence, Cyg X-1 appears only in one side of the FoV for a pointing strategy centered between Cyg X-1 and the Cyg A region; (H) for the hexagonal pattern and (GP) for a Galactic Plane scan. (H*) During the rev 875, the pointing strategy follows a pattern proposed by Wilm et al. in their AO-7 proposal. All this information is available on the dedicated ESA Web site http://integral.esa.int/isocweb.

### Table 1

| Revolution Number | Start           | End             | Useful Duration (ks) |
|-------------------|-----------------|-----------------|----------------------|
| 79–80 (5 × 5)     | 2003 Jun 7 00:59 | 2003 Jun 12 03:35 | 293                 |
| 210–214 (A)       | 2004 Jul 3 00:01 | 2004 Jul 17 00:25 | 709                 |
| 251–252 (A)       | 2004 Nov 3 14:23 | 2004 Nov 7 16:26 | 176                 |
| 259 and 261 (H)   | 2004 Nov 26 12:28 | 2004 Dec 3 15:43 | 143                 |
| 470 (EXO, H)      | 2006 Aug 19 09:19 | 2006 Aug 21 16:02 | 159                 |
| 486 (EXO, H)      | 2006 Oct 6 00:11 | 2006 Oct 8 07:55 | 160                 |
| 498–505 (GP)      | 2006 Nov 11 19:31 | 2006 Dec 4 06:20 | 535                 |
| 628–631 (A)       | 2007 Dec 4 19:05 | 2007 Dec 15 21:08 | 388                 |
| 673 (A)           | 2008 Apr 18 17:41 | 2008 Apr 19 22:09 | 54                  |
| 682–684 (A)       | 2008 May 14 08:13 | 2008 May 22 19:54 | 304                 |
| 739–746 (A)       | 2008 Nov 1 02:14 | 2008 Nov 24 05:25 | 551                 |
| 803–806 (A)       | 2009 May 11 08:27 | 2009 May 22 11:32 | 371                 |
| 875(H*) and 877(H) | 2009 Dec 12 16:18 | 2009 Dec 19 20:57 | 160                 |

**Notes.** In the first column, the letter after the revolution number indicates the dithering strategy used: (5 × 5) for the standard 5 × 5 pattern (see Section 2); (A) for a pointing strategy centered between Cyg X-1 and the Cyg A region; (H) for the hexagonal pattern and (GP) for a Galactic Plane scan. (H*) During the rev 875, the pointing strategy follows a pattern proposed by Wilm et al. in their AO-7 proposal. All this information is available on the dedicated ESA Web site http://integral.esa.int/isocweb.

### 3. STUDY OF THE SPECTRAL SHAPE

#### 3.1. The Total Mean Spectrum

The total mean spectrum gathers the whole set of available clean data (4 Ms of observation distributed over more than 6 years). It has been built by extracting one spectrum per revolution then summing them. Due to the impressive signal-to-noise ratio at low energy, we are unable to ensure that the response matrices are known with a sufficient precision. We have thus added 0.5% of systematic errors to the data during the fit procedure.

The data have been first fitted with a simple analytical cutoff power law and a Comptonization + reflection model (reflect*comptt in *xspec*). Residuals clearly show deviation from these models above 200–300 keV where an excess of emission appears above the model prediction. To go further, we keep a Comptonization law (+ its reflected component) in the low-energy part and focus on the high-energy emission. Following Laurent et al. (2011), we first try to model this additional component by a single power law. The fit converges toward a photon index of ∼1.8 (close to the 1.6 ± 0.2 value reported by these authors) but the χ² value remains unacceptable, with a huge contribution of the last channels. Indeed, the high-energy part does not follow such a power law: instead, the emission presents a rather sharp decrease after...
Table 2
Fit Parameters for the Total Averaged Spectra of Cyg X-1 Presented in Figure 2

| Model                | $\Omega$   | $kT$ (keV) | $\tau$ | $\alpha$ or $kT_{2}$ (keV) | $\tau_{2}$ | $\chi_{\text{red}}^{2}$ (DoF) |
|----------------------|-------------|------------|--------|----------------------------|------------|-------------------------------|
| Refl*Comptt          | 0.90 ± 0.3  | 75.0 ± 3   | 0.91 ± 0.03 |                               |            | 6.0 (37)                     |
| Refl*Comptt + power law | 0.88 ± 0.3  | 56 ± 3    | 1.2 ± 0.1 | 1.8 ± 0.2                   | 5.1 (35)   |                               |
| Refl*Comptt+Comptt   | 0.8 (fixed) | 38 ± 3    | 1.6 ± 0.15 | 123 ± 10                    | 0.5 (fixed)| 1.7 (36)                     |

Notes. Parameters obtained for the mean Cyg X-1 spectrum (all publicly available observations corresponding to 4 Ms of useful duration). 0.5% of systematic errors have been added to the data. Two parameters have been fixed in the second model to overcome some degeneracy.

Figure 1. Cyg X-1 averaged spectra for the whole data set (4 Ms of useful duration between 2003 and 2009). Approximations with Comptonization + reflection and two Comptonization models are represented by solid lines. 0.5% systematic errors have been added to the data. Upper limits are at 2$\sigma$ level. See Table 2 for model parameters.

(A color version of this figure is available in the online journal.)

700 keV and the source is not detected above 1 MeV. A better result is obtained when modeling this high-energy component by a second Comptonization region with a temperature around 100 keV. As several couples ($kT$, $\tau$) can reproduce the data, we fixed $\tau$ to 0.5 and obtained a best-fit value of $kT = 123$ keV (see Table 2). Figure 1 presents the observed spectrum with one and two Comptonization models. Even though the set of parameters proposed in Table 2 is only a possible solution, the two Comptonization model provides a good description of the data and more specifically of the curvature observed up to 1 MeV.

3.2. Flux, Hardness and Hardness versus Flux Evolution

The MeV emission may depend on the source spectral state or intensity. To follow potential changes in the source emission, we have analyzed in details each revolution and used the information to group observations corresponding to similar states.

Figure 2 displays the temporal evolution of Cyg X-1 in 30–70 keV energy range, with the fluxes averaged by revolution (100–200 ks timescale) and Figure 3 displays the evolution of the hardness (defined in the 30–120 keV range by $F_{70–120\text{keV}}/F_{30–70\text{keV}}$). In Figures 4 and 5, we present the same flux and hardness but detailed on timescales of a few days (with a resolution of one scw, i.e., $\sim$2000 s). These graphs illustrate clearly the variability of the source. The hypothesis of constant flux has been tested by $\chi^{2}$ tests and is strongly rejected for all periods (reduced $\chi^{2}$ always greater than 5.9 for a number of degrees of freedom ranging from 100 to 300). The variability appears to be chaotic but in both cases over a limited amplitude: the source is always detected and varies by a factor not greater than 3. We can recognize the usual temporal behavior of Cyg X-1 (see, e.g., Ling et al. 1987; Zdziarski et al. 2002). Note that the first period, which corresponds the lowest and softest
state in our sample, has been analyzed by Malzac et al. (2006). They identified the (rather unusual) source behavior as a mini or failed transition between soft and hard states, in a so-called intermediate state. However, no robust (that is, lasting more than a few hours) incursion in the SS can be reported during our observations and we conclude that Cyg X-1 was always in a hard (LH) or intermediate states.

Figure 6 displays the hardness as a function of the 30–70 keV source flux (revolution-averaged values). The hardness intensity plane can be divided into three regions corresponding to the main clusters of data points. Those three regions are outlined in Figure 6. The first two regions gather the points with hardnesses respectively below 0.24 and between 0.24 and 0.28, and, incidentally, correspond to the first part of the INTEGRAL mission (revolutions 79 to 261, i.e., 2003 June–2004 November).

In the third group, the flux levels span a broader range, extending toward higher values, but the mean hardnesses never decrease below 0.29. During this period, which covers more than 3 years (mid 2006 up to end of 2009), the source evolution consists of an intensity variation within a factor of ~2 without any visible change in the emission hardness (or spectral shape), so without notable change in the underlying processes. This behavior has already been observed in this source and is well known in transient sources.

Conversely, it is worth noting that different spectral shapes are observed for an unchanged intensity level in the 30–70 keV band. To illustrate both of these effects, we have superimposed in Figure 7 five spectra representative of the global course followed by the source in Figure 6 (the corresponding revolutions are identified in this figure by squares, numbered from 1 to 5).

We recognize the two modes of evolution already identified for this source on the ks timescale (Malzac et al. 2006): a pivoting of the spectral shape (spectra 2–4) and a change of luminosity at constant hardness (spectra 1 & 2 and 4 & 5). Note however that the pivot energy here is at ~45 keV (in the middle of the studied energy band by construction). It could be attributed to an increase of both temperature and optical depth of the Comptonizing medium. When combined, the two variability modes give rise to a global complex behavior in the hard X-ray domain, although the source remains in the HS (and intermediate states).

To study in more detail the spectral shape and its evolution in the high-energy part, we have to accumulate data corresponding to the same hardness.

### 3.3. Comparison of Different Averaged Spectra

Based on the three hardness levels represented in Figure 6, we have built the corresponding averaged spectra, hereafter referred to as “low hardness,” “mid hardness,” and “high hardness” samples, respectively. They are displayed in Figure 8, while best-fit parameters are given in Table 3. Similarly to the total spectrum, the data are modeled by a Comptonization law plus its reflection component (required when looking at residuals) and a second hotter Comptonization. The evolution of the slope in the low-energy part (in direct relation with the hardness) is clear, with an increase of the peak energy from ~50 keV to ~150 keV. This behavior is not related to the reflection component but...
appears as an evolution of the macroscopic parameters ($kT$ and $\tau$) of the Comptonizing medium, which both increase from the soft to the hard sample (see Table 3).

Looking now to the high-energy part, no significant emission is detected above 700 keV. A degeneracy between parameters being unavoidable, we choose to fix the second Comptonizing medium temperature and optical depth to 130 keV and 0.6, respectively, for all spectra, but free normalization factors.

Even though it represents only a possible description of our data, this model, involving a second (hotter and thinner) Comptonization medium with constant parameters $kT_2$ and $\tau_2$, provides an acceptable interpretation of the Cyg X-1 behavior in the hard X-ray domain. Even if other models could reproduce the data, such scenarios of two Comptonizing regions (or more generally, variable $kT_2$ and/or $\tau$) resemble those already applied in previous works to Cyg X-1 and several black hole binaries (see, for example, the Suzaku observations analyzed by Makishima et al. 2008, and references therein). Beyond the specific sets of best-fit parameter formally obtained, the inadequacy of the single Comptonization region suggests spatial and/or rapid temporal variation of the temperature or optical depth of the Comptonization region.

### 4. Annihilation Feature

Cyg X-1 is one of the brightest Galactic sources of hard X-rays up to several hundred keV and is therefore a good candidate for positron production. The excellent energy resolution of the SPI germanium detector makes it the best instrument to seek for potential annihilation signatures in the observed emission.

We have thus looked for any emission feature, narrow (10 keV FWHM) or broad (80 keV FWHM), transient (scw, i.e., $\sim$2 ks timescale) or more persistent (revolution, i.e., 1–2 day timescale). On the scw timescale, no significant emission is
Figure 6. Hardness vs. flux evolution. Each point represents (part of) a revolution. The solid straight line joins points in chronological order (from the triangle to the diamond symbols). The squares with numbers correspond to revolutions used in the next figure. Dashed lines represent the limits used to build different subsets of data (see the text and Figure 8). (A color version of this figure is available in the online journal.)

Figure 7. Individual spectra illustrating the spectral evolution. The three middle spectra illustrate the pivoting of the shape at constant flux, while the lowest (#1) and the highest (#5) correspond to a change in intensity with similar spectral shape. (A color version of this figure is available in the online journal.)

Figure 8. Cyg X-1 averaged spectra for the three hardness levels. Solid lines represent a model with two Comptonization models. Dotted lines correspond to the first component (see Table 3 for the parameters) and dashed lines to the second one (with $kT$ fixed to 130 keV and $\tau$ fixed to 0.6). Upper limits are at a 2$\sigma$ level. (A color version of this figure is available in the online journal.)

reported with 2$\sigma$ upper limits of $(2–3) \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ and $(0.5–1) \times 10^{-2}$ photons cm$^{-2}$ s$^{-1}$ for a narrow and a broad line, respectively. On the revolution timescale, no significant excess above the continuum contribution is found, with upper limits ranging between $(3–6) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ and $(0.7–1.1) \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$ according to the revolution duration. Finally, considering the whole set of data (4 Ms), persistent emission features, if any, should be below $6 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ and $1.3 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$.

5. COMPARISON WITH OTHER INSTRUMENTS

We now compare our observations with the available data in the MeV region. From Figure 9, we can see that our “high hardness sample” observations have a spectral shape that is very close to that of the HS mean spectrum reported by McConnell et al. (2002) from CGRO/COMPTEL and OSSE instruments. To compare the whole set of data (INTEGRAL/SPI + CGRO/COMPTEL+OSSE), we use a model consisting in a cut-off power law plus a broken power law with the first index fixed to $-1$ (to avoid any contribution in the low-energy part).

Imposing the same photon index for the cutoff power laws, the fit procedure converges toward slightly different cutoff energies ($\sim 140$ and 160 keV, for SPI and OSSE data, respectively, no contribution in COMPTEL range). We also impose a common second photon index in the broken power law and obtained $3.4 \pm 0.5$, while the energy break reflects the true difference between the spectra: close to 900 ($\pm 100$) keV in the CGRO data, it means that this component is based essentially on the COMPTEL points. Around 420 ($\pm 25$) keV in the SPI data, it allows us to recover the additional emission above the low-energy component, the very soft index limiting its extension toward high energies.

In conclusion, even if the SPI data do not show significant emission above 1 MeV, the upper limits are marginally consistent with the non-thermal tail observed at several MeV by CGRO/COMPTEL. We note however that this emission is not taken into account by the two-zone thermal Comptonization model proposed above, which would require an additional

\[ a \times b \]
component to fit the COMPTEL data. The overall good agreement between the SPI and OSSE spectra indicates that the average spectral properties in the HS have remained constant between the two epochs.

Recently, Laurent et al. (2011) presented a stacked spectrum of Cygnus X-1 obtained using the IBIS data during nearly the same observation period as ours. IBIS is composed of two position-sensitive detector layers ISGRI (CdTe, 15–1000 keV; Lebrun et al. 2003) and PICsIT (CsI, 200 keV–10 MeV; Labanti et al. 2003). These two detectors are usually used independently to produce spectra and light curves, but can also be used in coincidence to detect high energy photons scattered in one detector and absorbed in the second (“Compton-mode”, see details in Forot et al. 2007). Laurent et al. (2011) used the IBIS/ISGRI data up to ∼400 keV and IBIS/Compton-mode at higher energies. Figure 10 compares our averaged SPI spectra with the results of Laurent et al. (2011). We note that most of the published results from IBIS actually use only the ISGRI detector. With the recent versions of the public software, the results from IBIS/ISGRI are generally compatible with those of SPI. This good agreement is confirmed by our comparison of the stacked SPI and IBIS/ISGRI spectra. At higher energies, however, the results are clearly different: the SPI fluxes are lower than the IBIS/Compton-mode points by a factor of about five at least. The origin of this disagreement is unclear. We were not able to go further in the analysis of the discrepancy as there are very few published results from IBIS/Compton-mode.

6. SUMMARY AND CONCLUSIONS

We used 4 Ms of INTEGRAL SPI data to study the emission of Cyg X-1 from 20 keV to the MeV region. While the source has been essentially detected in the HS, it presents complex variability on all timescales. We have studied the luminosity and hardness evolution of the source above 20 keV, on the scw (2000 s) and revolution (1–2 days) timescales. The revolution-averaged data give a nice picture of the long term source behavior. A change by a factor of 2–3 in luminosity can be accompanied either by a significant softening in the 20–150 keV domain (see Figure 8) or by the same spectral shape just moved up and down.

Then, in order to improve the photon statistics at high energies we combined observations to produce long exposure time average spectra. The analysis of the stacked spectra reveals that the emission of Cyg X-1 extends up to ∼700 keV but presents a sharp cutoff around that energy. Whatever the criterion we used to build averaged spectra (low/mid/high hardness, low/high intensity, all data), no emission can be detected above 1 MeV.

Nevertheless, a single Comptonization model does not provide a good description of the overall spectral shape. We have shown that a two temperature model provides a good fit of the SPI data, with a minimum of free parameters (τ and kT of the second Compton component can be considered as constant over time).

In a final step to investigate the high-energy emission, we compare all the data available above 300 keV for Cyg X-1 in the last two decades and conclude that while our SPI upper limits are marginally compatible with the soft power law reported by COMPTEL in the 1990s (McConnell et al. 2002), they clearly
disagree (lower by a factor $\sim 5$) with the recently reported IBIS/Compton-mode emission (Laurent et al. 2011).

In other words, the presence of a non-thermal mechanism participating in the power supply cannot be excluded, but our results contradict the presence of a hard (polarized or not) power-law emission.

A last point concerns the potential emission linked to the positron production: no positive detection has been found in a narrow (10 keV) and a broad (80 keV) channel, on 2 ks and day timescales, as well as in the total data set.

The question of the origin and the nature of the HS high-energy emission remains thus of prime interest. Cyg X-1 is clearly the best target in which to investigate it. Since no mission operating above 300 keV is expected for a while, the only hope is that the INTEGRAL instruments will be able to accumulate a few more Ms of data on this important target to resolve the matter once and for all.

The INTEGRAL SPI project has been completed under the responsibility and leadership of CNES. We are grateful to ASI, CEA, CNES, DLR, ESA, INTA, NASA, and OSTC for support. We thank A. A. Zdziarski for providing us with GRO/COMPTEL and OSSE data.

REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Bassani, L., Dean, A. J., Di Cocco, G., Perotti, F., & Stephen, J. B. 1989, ApJ, 343, 313
Done, C., Gierliński, M., & Kubota, A. 2007, A&AR, 15, 1
Forot, M., Laurent, P., Lebrun, F., & Limousin, O. 2007, ApJ, 668, 1259
Gierlinski, M., Zdziarski, A. A., Done, C., et al. 1997, MNRAS, 288, 958
Gierlinski, M., Zdziarski, A. A., Poutanen, J., et al. 1999, MNRAS, 309, 496
Jensen, P. L., Clausen, K., Cassi, C., et al. 2003, A&A, 411, L7
Jourdain, E., & Roques, J. P. 2009, ApJ, 704, 17
Labanti, C., Di Cocco, G., Ferro, G., et al. 2003, A&A, 411, L149
Laurent, P., Rodriguez, J., Wilms, J., et al. 2011, Science, 332, 438
Lebrun, F., Leray, J.P., Lavocat, P., et al. 2003, A&A, 411, L141
Liang, E. P., & Nolan, P. L. 1984, Space Sci. Rev., 38, 353
Ling, J. C., Mahoney, W. A., Wheaton, W. A., & Jacobson, A. S. 1987, ApJ, 321, L117
Makishima, K., Takahashi, H., Yamada, S., et al. 2008, PASJ, 60, 585
Malzac, J., Petrucci, P. O., Jourdain, E., et al. 2006, A&A, 448, 1125
McConnell, M. L., Zdziarski, A. A., Bennett, K., et al. 2002, ApJ, 572, 984
Roques, J. P., Schanne, S., Von Kienlin, A., et al. 2003, A&A, 411, L91
Vedrenne, G., Roques, J. P., Schonfelder, V., et al. 2003, A&A, 411, L63
Zdziarski, A. A., Poutanen, J., Paciesas, W. S., & Wen, L. 2002, ApJ, 578, 357