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Near-infrared, optical, and X-ray observations of the anomalous X-ray pulsar 4U 0142 + 61

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Abstract

We present results from the simultaneous observations of an anomalous X-ray pulsar (AXP) 4U 0142 + 61 on Sep. 2003. We used *RXTE*, *Subaru*, and *UH88* telescopes to cover X-ray, near-infrared (NIR) (JHK′), and optical (BVRI) bands, respectively. We obtained a simultaneous broadband spectrum for the first time among AXPs. We found NIR excess in the spectrum, which may be another component different from the optical one. We also found a R band dip. We discuss the broadband spectrum covering the optical and X-ray bands in the framework of a self absorbed synchrotron emission from the magnetosphere of magnetar. We also discuss about the R band dip feature, which could put a restriction on the emission models of magnetars.

Keywords: Neutron star; Anomalous X-ray pulsar; Magnetar

1. Introduction

The anomalous X-ray pulsars (AXPs) are a small group of X-ray pulsars (see Mereghetti et al., 2002 for a review). They are not likely to be accretion-powered pulsars, because the fluxes of the optical counterparts are too small for high-mass binary companions, the Doppler modulation due to the binary motion has not yet been found, and the pulse timing peculiar in the accretion disk (large timing noises and/or persistent spin-up periods) have not been found. They are also not rotation-powered pulsars, because the observed X-ray luminosities ($L_X \sim 10^{34}$–10^{36} ergs s^{-1}) exceed the spin-down energy loss rates of neutron stars ($\dot{E} = 4\pi^2 I\dot{P}/P^3 \sim 10^{32.6}$ ergs s^{-1}). AXPs are also characterized as follows: (1) X-ray spectra are fit well by the model consisting of a blackbody (∼0.4 keV) and a soft power-law function ($\Gamma \gtrsim 2$); (2) radio emissions have not been detected, yet; (3) slow rotation periods (5–12 s); (4) magnetic fields estimated by P and $\dot{P}$ are $B \sim 10^{14}$–10^{15} G. It is the prevailing hypothesis that AXPs and SGRs (soft gamma repeaters) are solitary neutron stars with ultra-strong magnetic fields (10^{14}–10^{15} G), referred to as "magnetars". X-ray photons are produced in this model by the release of the strong magnetic field energy stored in the neutron star crust, or in a twisted internal magnetic field of neutron stars (Thompson and Duncan, 1996, Thompson and Duncan, 2001).

4U 0142 + 61 has been one of the prototypes of AXPs (Mereghetti and Stella, 1995). Its pulse period is 8.7 s (Israel et al., 1994). The optical counterpart was

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discovered by Hulleman et al. (2000). The Spectral Energy Distribution (SED) was found to be strange; There were K band excess and B band cut-off (Hulleman et al., 2004). The optical pulsation was discovered by Kern and Martin (2002), which suggests that the optical emission comes from the magnetosphere of the neutron star. Recently Morii et al. (2005) showed that 4U 0142 + 61 is not a stable rotator by finding a pulse profile change possibly associated with a glitch. It is reminiscent of the X-ray outburst of the AXP 1E 2259 + 586, when the near-infrared (NIR) flux flare, glitch, and pulse profile change were observed (Kaspi et al., 2003). Therefore, the simultaneous multi-color photometry with monitoring the X-ray activity is necessary to obtain the reliable NIR-optical spectrum of 4U 0142 + 61.

Some theories to explain the NIR-optical emissions from magnetars were proposed. Eichler et al. (2002) proposed that magnetospheric currents above the surfaces of magnetars radiate coherent emission in the infrared or optical band. Ertan and Cheng (2004) showed the optical emission of 4U 0142 + 61 can be accounted for by the magnetar outer gap model. Lu and Zhang (2004) proposed a maser curvature emission mechanism in the presence of curvature drift at the polar cap of magnetar.

2. Observations

We performed the near-simultaneous observations of AXP 4U 0142 + 61 in NIR (JHK′) and optical (BVRI) bands, using Subaru and UH88 telescopes, while the X-ray activities were monitored by RXTE. We used `GoodXenon_with_Propane` mode of PCA detector to get high time resolution(∼μs). Fortunately, the photometric conditions were good for all telescope observations. Summary of these observations are shown in Table 1.

3. Analysis

The combined images of UH88/Subaru were made by the standard image analysis procedure; The raw images were subjected to the subtraction of the bias/dark images, and they were flat-fielded by the observations themselves. Then they were summed with rejecting instrumental bad pixels and cosmic rays. We used IRAF/PHOT package for the photometry. We used some stars taken in the same frames as 4U 0142 + 61 for the calibration of the instrumental magnitude, since their magnitude were listed in the catalog.

The raw RXTE data were subjected to the following event selection. We selected the events during the Good Time Intervals and when the PCU2 and PCU3 were active. In addition we rejected the duration when the count rate of the particle backgrounds were high. Then the events of 3.0–10.0 keV were selected. The light curves, pulse frequency, and pulse profiles were checked after the barycentric correction of the time.

4. Results

There were no burst activities, no flux change, and no significant pulse profile changes among the two RXTE

Table 1
Summary of our observations of 4U 0142 + 61

Instrument	Bands	Dates (UT)	Exposures (ks)	Seeings (″)
UH88/OPTIC	IRVB	2003 Sep. 3	3.0, 4.8, 4.8, 3.3	0.7, 0.7, 0.8, 0.9
UH88/OPTIC	IRVB	2003 Sep. 4	4.5, 4.8, 4.8, 4.2	0.6, 0.8, 0.8, 0.7
Subaru/IRCS	K′	2003 Sep. 8	0.8	0.6
Subaru/IRCS	K′ H J	2003 Sep. 9	1.1, 1.6, 2.2	0.4, 0.5, 0.4
RXTE	X-ray	2003 Sep. 3, 8	15.1, 15.4	–

Table 2
Magnitudes of 4U 0142 + 61

Band	Days (UT)	Magnitude	Catalog[a]	Difference[*]	Catalog stars (ID)
K′	Sep. 9	19.85 ± 0.11	Variable[b]		115, 109
H	Sep. 9	20.60 ± 0.08	–		115, 109
J	Sep. 9	22.07 ± 0.10	–		115, 109
I	Sep. 3 + 4	23.973 ± 0.093	23.840 ± 0.040	1.4σ	106, 110, 126, 134
R	Sep. 3 + 4	25.556 ± 0.177	24.890 ± 0.050	4.6σ	126, 134, 136, 142
V	Sep. 3 + 4	25.316 ± 0.134	25.620 ± 0.080	1.8σ	106, 110, 126, 134
B	Sep. 3 + 4	>27.2 (3σ)	>27.4 (3σ)		126, 136, 142

IRVB (K′HJ) bands were determined by the relative photometry with the stars (the rightest column) listed in the Table 3 of Hulleman et al. (2004) (2MASS catalog). These aperture diameters were 1.65 (1.05)″.
[a] Magnitudes listed in the Table 3 of Hulleman et al. (2004).
[b] $K = 19.68 \pm 0.05$ on 1999 Feb. 7 + 8, $K_s = 20.15 \pm 0.08$ on 2001 Oct. 30, and $K_s = 19.85 \pm 0.04$ on 2002 Dec. 18 (Hulleman et al., 2004).
[*] Significance of the difference between the magnitudes of our results and Hulleman et al. (2004).