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Chandra observations of LS I +61 303

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We present here X-ray observations of the high mass X-ray binary LS I +61 303 carried out during 50 ks with the ACIS-I array aboard the *Chandra* X-ray Observatory. The source count rate and hardness ratio was found to be moderately variable on timescales of hours, confirming previous results. No clear correlation between the hardness ratio and the total count rate is present in the data, in contrast to previous results. We produced a single spectrum of the source, which could be properly fitted with an absorbed power-law model after considering pileup effects. The resulting parameters are $N_{\rm H} = (0.68 \pm 0.06) \times 10^{22}$ cm^{-2} and $\Gamma = 1.25 \pm 0.09$. The flux of the source in the 0.3–10 keV range is $(7.8 \pm 2.2) \times 10^{-12}$ erg cm^{-2} s^{-1}. Assuming a distance to the source of 2.0 kpc the intrinsic X-ray luminosity is found to be $L_{\rm X~(0.3-10~keV)} = (3.7 \pm 1.1) \times 10^{33}$ erg s^{-1}. Hints of extended and hard X-ray emission forming a ring-like structure around LS I +61 303 are also found. If this extended X-ray emission is produced by synchrotron radiation, efficient particle acceleration up to scales of $\sim 10^4$ AU takes place in LS I +61 303.

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1. Introduction

LS I +61 303 is a High Mass X-ray Binary associated with the galactic plane variable radio source GT 0236+610 [1]. Optical observations show that the system may be formed by a rapidly rotating early type B0V star, with a stable equatorial disk and mass loss, and a compact object orbiting it every 26.5 d [2]. The periastron takes place at phase 0.23 and the eccentricity is 0.72±0.15 [3]. There is yet uncertainty as to what kind of compact object, a black hole or a neutron star, is part of the system [3], although very recent results seem to suggest that the system is composed of an energetic non-accreting pulsar [4]. Spectral line observations of the radio source give a distance of 2.0±0.2 kpc [5].

One of the most unusual aspects of its radio emission is the fact that it exhibits quasi-periodic nonthermal outbursts on average every $P_{\rm orb}$=26.4960±0.0028 d [6, 7] and the orbital phase of the maximum varies between phase 0.45 and 0.95 (assuming T_0=JD 2,443,366.775). This periodicity corresponds to the orbital period of the binary system [2] and has also been detected in $UBVRI$ photometric observations [8], in the infrared domain [9], in soft X-rays [10] and in the Hα emission line [11]. An extended jet-like and apparently precessing radio emitting structure at angular extensions of 0.01–0.05 arcsec has been reported [12, 13]. In spite of the fact that jet-like structures are commonly associated to microquasars, VLBA images obtained during a full orbital cycle show a changing morphology of LS I +61 303 [4], which may be consistent with a model based on the interaction between the relativistic wind of a non-accreting pulsar and the wind of the stellar companion [14].

Recently, the MAGIC Cherenkov telecope has detected LS I +61 303 at very high ($\gtrsim$100 GeV) γ-ray energies [15]. LS I +61 303 and LS 5039 [16, 17] share the quality of being the only two known high-energy emitting X-ray binaries that are spatially coincident with sources above 100 MeV listed in the Third EGRET catalog [18].

Here we report on a preliminary analysis of a 50 ks observation of LS I +61 303 performed by the *Chandra* X-ray Observatory, the main aim of these observations being the detection of possible extended X-ray structures around the source.

2. Previous results from X-ray observations of LS I +61 303

ROSAT and VLA observations carried out during a complete orbital cycle showed that the X-ray and the radio emission appear anticorrelated, with the former peaking before the latter [19]. The unabsorbed flux in the 0.07–2.48 keV band varied between 2×10^{-13} and 3×10^{-12} erg cm^{-2} s^{-1} for an assumed column density of $N_{\rm H} = 0.84\times10^{22}$ cm^{-2}. *ASCA* observed LS I +61 303 and measured an unabsorbed flux of (4–6)$\times10^{-12}$ erg cm^{-2} s^{-1} in the energy range 0.5–10 keV, assuming $N_{\rm H} = 0.6\times10^{22}$ cm^{-2} and a power-law photon index of 1.7–1.8 [20]. The source has also been observed twice with *BeppoSAX*, and detected with fluxes in the range (5–14)$\times10^{-12}$ erg cm^{-2} s^{-1}, using $N_{\rm H} = 0.8\times10^{22}$ cm^{-2}, and with spectra consistent with a power-law of photon index in the range 1.6–1.8. Detailed *RXTE* observations confirmed the previously found anticorrelation between the radio and the X-ray emission within the same orbital cycle, with a flux varying in the range (6–20)$\times10^{-12}$ erg cm^{-2} s^{-1} [21]. In general, the flux presented by this source is about four to five orders of magnitude lower than the Eddington limit for a neutron star.

XMM-Newton observations of LS I +61 303 consist of 5 short pointings carried out during 2002, and a 50 ks run conducted in January 2005. The analysis of the first 5 pointings has been reported in [22]: the spectra are properly fitted with an absorbed power-law with no evidence of spectral lines and the hydrogen column density obtained after averaging all the data is $N_{\rm H} = 0.5 \times 10^{22}$ cm^{-2}. The obtained 2–10 keV flux is found to be variable with the orbital phase, having a minimum at periastron and becoming approximately three times higher at phases larger than 0.5, where the maximum of gamma-ray emission is located [15]. The obtained photon index is also variable and in the range 1.5–1.8.

The analysis of the 50 ks pointing has been reported in Sidoli et al. [23]. The flux along the observation takes values similar to those found with *BeppoSAX*, and the hydrogen column density is compatible with the one discussed above. During this long observation, taken around phase 0.6, the authors find evidence for a rapid change in flux and hardness ratio: the source flux decreased by a factor of $\sim$3, accompanied by a significant drop in hardness ratio, within about 1000 s. This kind of variability (the source is harder when is brighter) is also present when comparing observations performed in different epochs and even with different satellites. Interestingly, this behavior is also observed in LS 5039 [24]. In summary, there is X-ray emission along all orbital phases, although significant flux and photon index changes take place on long and short timescales.

3. *Chandra* observations and analysis

We observed LS I +61 303 with the *Chandra* X-ray Observatory using the standard ACIS-I setup in VF mode during a total of 50 ks from 2006 April 7 22:09 UT to April 8 12:34 UT (MJD 53832.9229–53833.5236). Since we were interested on both spectral and spatial information, to minimize possible pileup effects we observed the source at the orbital phase 0.0, which corresponds to a relatively faint state of the X-ray emission.

We show in Fig. 1 the *Chandra* image of the field around LS I +61 303. The readout streak has been removed from the original image, we have applied a factor of two binning and smoothed the resulting image with a Gaussian function for a better display. In addition to LS I +61 303 and several faint X-ray sources, two relatively bright objects were clearly detected. These sources were first detected in X-rays by *Einstein* and *ROSAT* and identified with the stars BD+60 536 (G2 V) and HD 16429 (O9.5 I), respectively [25, 26]. We focus here on LS I +61 303.

3.1 X-ray lightcurves

The LS I +61 303 background subtracted lightcurves obtained by *Chandra* in three different energy ranges are shown in Fig. 2. The soft (0.3–1.7 keV) and hard (1.7–10 keV) energy ranges have been chosen to divide the total energy range in two equal intervals in logarithmic scale. We have also computed the hardness ratio using the count rates in the two energy ranges. The lightcurves show flux changes on timescales of a few hours, with total amplitude variations of about a factor of two. This kind of moderate variability was first observed with *ASCA*, which detected source variations of about 50% on timescales of half an hour [21]. More recently, the analysis of archival *BeppoSAX* observations, carried in 1997, has shown also short-term variability [23]. It is interesting to note that small amplitude radio flares with a recurrence period of about 1.5

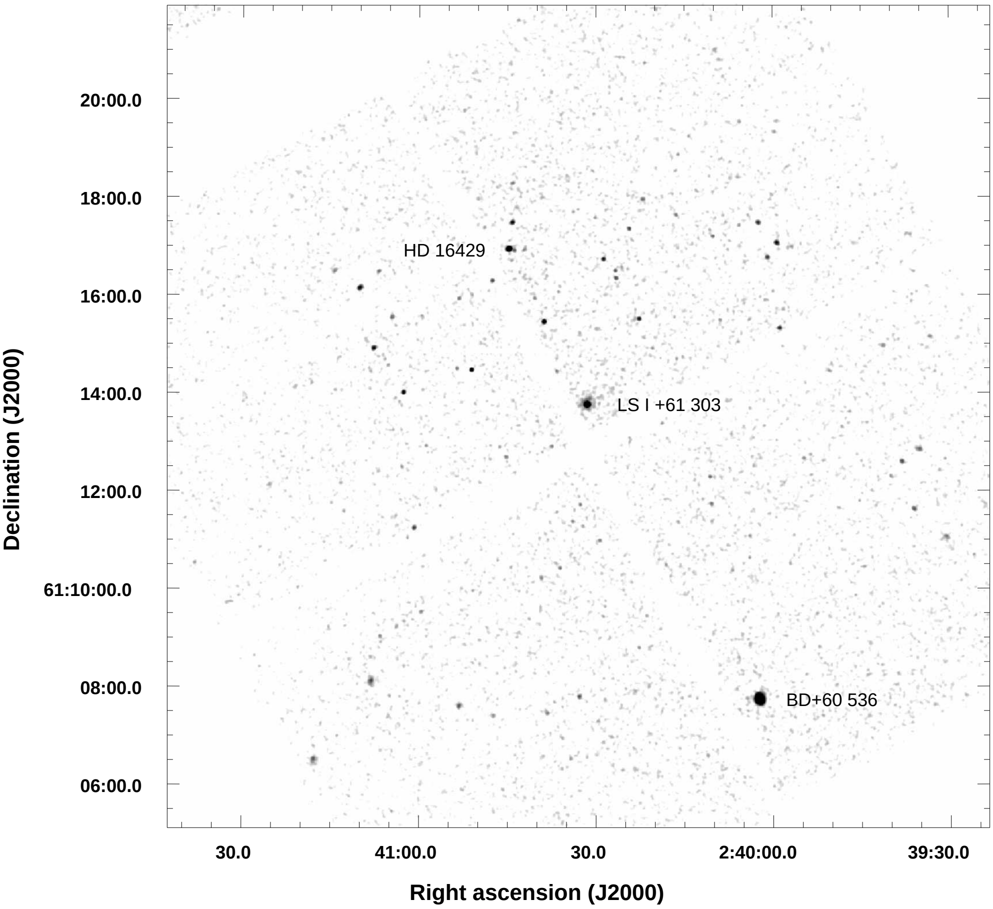

Figure 1: *Chandra* image of the field around LS I +61 303. The readout streak has been removed. A binning factor of 2 and a smoothing with a Gaussian function with a 3 pixel kernel have been used. Faint emission around LS I +61 303 can be marginally seen. The stars HD 16429 and BD+60 536, detected in earlier observations, have been labeled.

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hours have also been detected in LS I +61 303 [27]. Finally, the hardness ratio is also variable between 1 and 4, but with no clear correlation with the total count rate, contrary to what was observed in the long *XMM-Newton* pointing [23].

3.2 X-ray spectrum

The spectral analysis has been carried out using Sherpa (CIAO 3.3.0.1). Although the count rate shows a factor of two variability and the hardness ratio is also variable, the lack of correlation with the total count rate made us consider the whole data set together for a preliminary spectral analysis. We first tried to fit the data with an absorbed power-law model, which provided a hydrogen column density of $N_{\rm H} = (0.49 \pm 0.04) \times 10^{22}$ cm^{-2}, a photon index $\Gamma = 0.83 \pm 0.04$, and an unabsorbed flux in the range 0.3–10 keV of $F_{\rm X} = (3.70 \pm 0.05) \times 10^{-12}$ erg cm^{-2} s^{-1} (reduced $\chi^2 = 1.14$). We show in Fig. 3-left the data together with the spectral fit. There is a clear deviation from the power law above 7 keV. Since the expected pileup fraction for a source with ~ 0.15 cts s^{-1} is about a 15%, pileup effects on the observed spectrum can be significant.

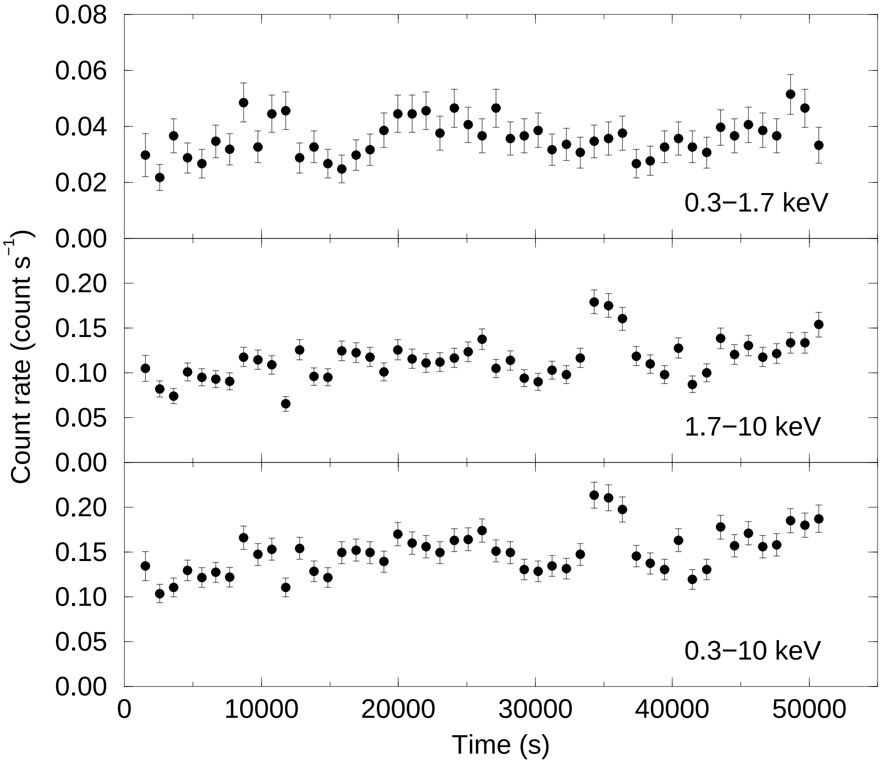

Figure 2: LS I +61 303 lightcurves obtained with *Chandra* in three different energy bands (soft, hard and total, from top to bottom) after background subtraction and binning with 1024 s. The time origin corresponds to 2006 April 7 at 22:09:00 UT (MJD 53832.9229), and the observation length is 50 ks. Total count rate variations of a factor of two on timescales of a few hours are clearly seen.

We then used the pileup model implemented in Sherpa [28]. We fixed the parameter concerning the fraction of flux falling into the pileup region to 95%, and obtained for the grade migration parameter $\alpha = 0.31 \pm 0.10$, and for the remaining parameters $N_{\rm H} = (0.68 \pm 0.06) \times 10^{22}$ cm^{-2}, $\Gamma = 1.25 \pm 0.09$, pileup fraction 15%, and $F_{\rm X} = (7.8 \pm 2.2) \times 10^{-12}$ erg cm^{-2} s^{-1} (reduced $\chi^2 = 0.8$). We show in Fig. 3-right the data together with the much better spectral fit obtained using the pileup model. Assuming a distance to the source of 2.0 kpc the intrinsic X-ray luminosity is found to be $L_{\rm X~(0.3-10~keV)} = (3.7 \pm 1.1) \times 10^{33}$ erg s^{-1}.

3.3 Imaging

We were mainly concerned with the presence of possible diffuse extended X-ray emission around LS I +61 303. We have therefore created the instrument point spread function (PSF) using ChaRT and MARX to simulate the most accurate PSF, taking into account the proper source spectrum including the effect of pileup. We then obtained surface brightness radial profiles of the source and the PSF in the energy range 0.3–10 keV. We have found that there is a 3σ excess in a region at $\sim 8''$ from the source center. This is shown in Fig. 4. Although it could be a statistical artifact, we note that the excess persists when we change the bins adopted to compute the surface brightness. The total excess of counts over the PSF between 7 and $13''$ from the image center is 34 ± 6, which is about a 0.5% of the total source counts. Although the low statistics do not allow

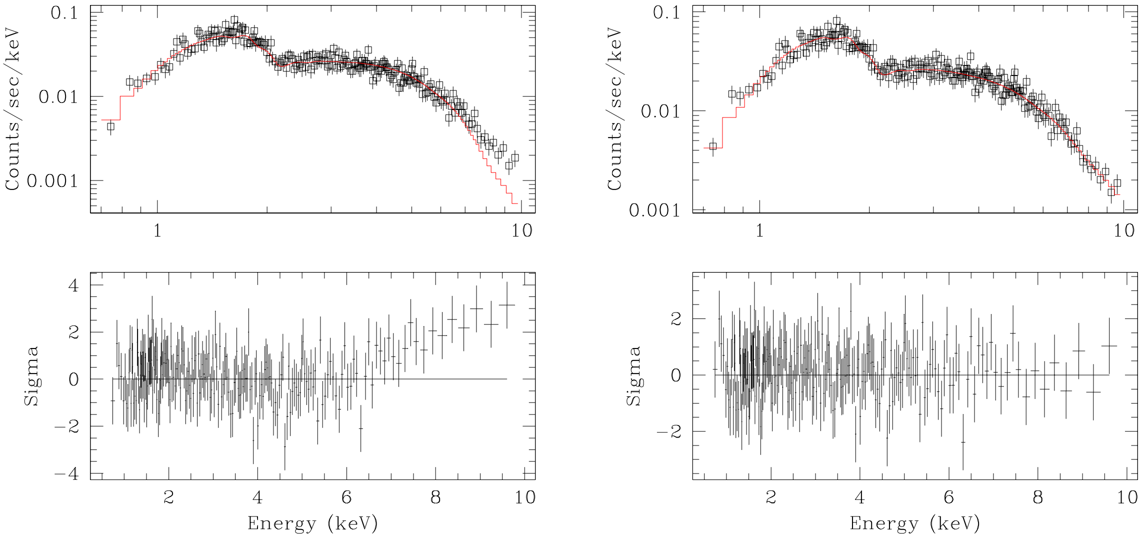

Figure 3: Left: Spectrum of LS I +61 303 (open squares) fitted with an absorbed power-law model (solid line). A significant excess is seen above 7 keV in the residuals shown below. **Right:** The same spectrum but fitted taking into account pileup in the modeling. The excess is not present in the residuals.

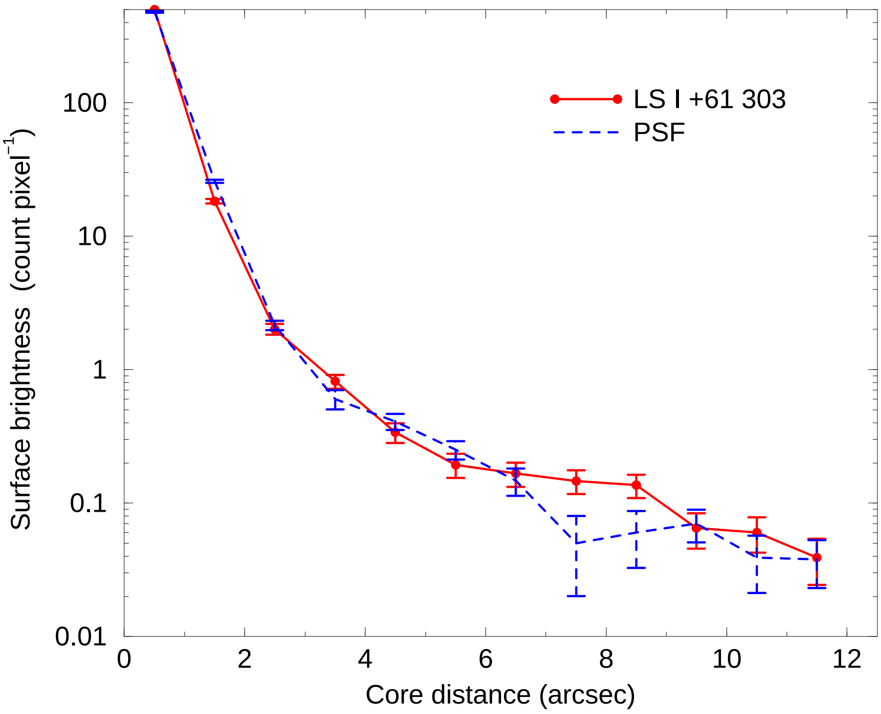

Figure 4: Surface brightness distribution of LS I +61 303 (red filled circles) compared to PSF one (dashed line).

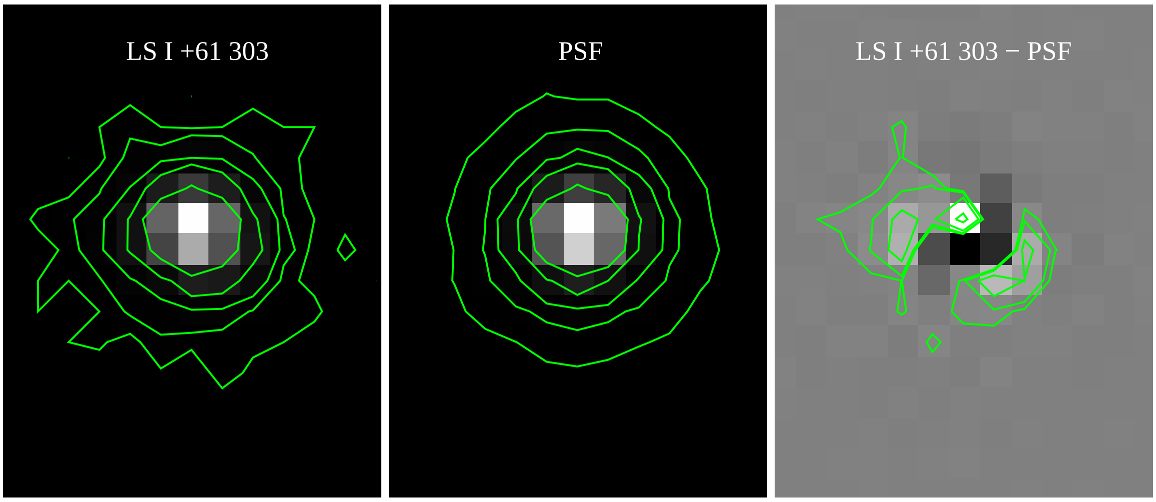

Figure 5: Images and contours of LS I +61 303, the PSF and the residuals obtained after subtracting the PSF from the LS I +61 303 image.

us to obtain a good spectrum determination, the extended emission seems to be hard. We remark that these are preliminary results.

We show in Fig. 5-left the central part of the source image, spanning $\sim 6'' \times 8''$. We have overlaid on the image a contour plot, which displays a shape that seems to slightly depart from a circular one. The PSF image is shown in Fig. 5-middle, both in greyscales and contours, presenting a nearly circular shape in contrast to the LS I +61 303 one. We finally show the residual image, after subtracting the PSF from the source, in Fig. 5-right. There seems to be an excess of counts at a few pixels from the image core roughly along the horizontal direction.

4. Summary and discussion

We have presented here the results of a preliminary analysis of recent *Chandra* observations of LS I +61 303 taken in April 2006. The X-ray emission shows moderate variability in the flux and hardness ratio on timescales of a few hours. No clear correlation between the X-ray flux and the hardness ratio has been found. The spectrum seems to be non-thermal, being well described with an absorbed power law, after considering pileup effects. We note that this spectrum is harder than in previous observations [22, 23]. The most intriguing result is the strong hint of excess at $\sim 8''$ from the center of the source. Excesses at smaller scales might be present, although at this stage it is unclear whether they are real or not. Clearly they deserve further investigation.

The hard spectrum of the extended component at $\sim 8''$ from the source center excludes the possibility of it to be a dust-scattered halo, which would produce a softer spectrum [29, 30]. The detected extended emission is therefore intrinsic to the source. At a distance of 2 kpc $\sim 8''$ correspond to 1.6×10^4 AU. Due to its typical timescales, X-ray synchrotron emission seems to be a more suitable mechanism than inverse Compton to produce such extended structure, although the difficulties associated with extracting spectra of the extended emission prevent precise statements regarding the origin of the emission. It is unclear whether the diffuse X-ray emitting electrons far away from the binary system are accelerated by a jet, favoring the microquasar scenario, or by something else. Nevertheless, it appears that LS I +61 303 can power efficient particle acceleration not only within the binary system on scales below 1 AU [15], but up to very large distances of $\sim 10^4$ AU from it.

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