OBSERVATION OF ENHANCED X-RAY EMISSION FROM THE CLASSICAL T TAURI STAR AA TAU DURING THE TRANSIT OF AN ACCRETION FUNNEL FLOW.

N. Grosso, *Observatoire astronomique de Strasbourg, Université Louis-Pasteur, CNRS, 11 rue de l'Université, 67000 Strasbourg, France*, J. Bouvier, T. Montmerle, *Laboratoire d'astrophysique de Grenoble, Université Joseph-Fourier, CNRS, 414 rue de la Piscine, 38041 Grenoble, France*, M. Fernández, *Instituto de Astrofísica de Andalucía, CSIC, Camino Bajo de Huétor 50, 18008 Granada, Spain* , K. Grankin, *Ulugh Beg Astronomical Institute of the Uzbek Academy of Sciences, Astronomicheskaya 33, 700052 Tashkent, Uzbekistan*, M.R. Zapatero Osorio, *Instituto de Astrofísica de Canarias, vía Láctea s/n, 38205 La Laguna, Spain*.

Classical T Tauri stars are young solar-type stars accreting material from their circumstellar disks. Thanks to a favorable inclination of the system, the classical T Tauri star AA Tau exhibits periodic (∼8 days) optical eclipses as the warped inner disk edge occults the stellar photosphere. We intend to observe the X-ray and UV emission of AA Tau during the optical eclipses with the aim to localize these emitting regions on the star. AA Tau was observed for about 5 h per XMM-Newton orbit (2 days) over 8 successive orbits to cover 2 optical eclipse periods. The XMM-Newton optical/UV monitor (OM) simultaneously provided UV photometry. Some V-band photometry was also obtained from the ground during this period in order to determine the dates of the eclipses. Two X-ray and UV measurements were secured close to the eclipse center. The UV flux is the highest just before the eclipse starts and the lowest towards the end of it. UV flux variations amount to a few 0.1 mag on a few hours timescale, and up to 1 mag on a week timescale, none of which are correlated with the X-ray flux. We model it with a weekly modulation (inner disk eclipse), plus a daily modulation, which suggests a non-steady accretion. No such eclipses are detected in X-rays. Within each 5 h-long observations, AA Tau has a nearly constant X-ray count rate. On a timescale of days to weeks, the X-ray flux varies by a factor of 2–8, except for one measurement where the X-ray count rate was nearly 50 times stronger than the quiescent level even though photoelectric absorption was the highest at this phase, and the plasma temperature reached 60 MK, i.e., a factor of 2–3 higher than in the other observations. This X-ray event, observed close to the center of the optical eclipse, is interpreted as a flare. We identify the variable column density with the low-density accretion funnel flows blanketing the magnetosphere. The lack of X-ray eclipses indicates that X-ray emitting regions are located at high latitudes. Furthermore, the occurrence of a strong X-ray flare near the center of the optical eclipse suggests that the magnetically active areas are closely associated with the base of the high-density accretion funnel flow. We speculate that the impact of this free falling accretion flow onto the strong magnetic field of the stellar corona may boost the X-ray emission.

1 X-ray and UV properties of AA Tau

We observed AA Tau for about 5 h per XMM-Newton orbit (2 days) over 8 successive orbits (PI: J. Bouvier), which covers two optical eclipse periods (8.22 days), in order to demonstrate the reproducibility of the phenomenon from one rotational cycle to the next. These observations were partly reported in Schmitt & Robrade (2007), who associated the UV minimum with the optical eclipse. Here we summarize the results based on the combined X-ray, optical/UV (XMM-Newton), and ground-based optical observations, obtained by Grosso et al. (A&A, submitted). Within each observations, AA Tau exhibited a nearly constant X-ray flux. On a timescale of days to weeks, the X-ray flux varies by a factor of 2–8, except between observations #1 and #2, where the EPIC count rate jumped in less than 2 days to a level 50 times stronger than the quiescent level (Fig. 1). Then, the EPIC count rate decayed in less than 2 days to a level only 2.5 times stronger than the quiescent level. Such large amplitudes in the X-ray fluxes of young stellar objects are usually observed during X-ray flares, which have typical light curves with fast rise and peak phase, and slower (exponential) decay phase, associated with fast heating and

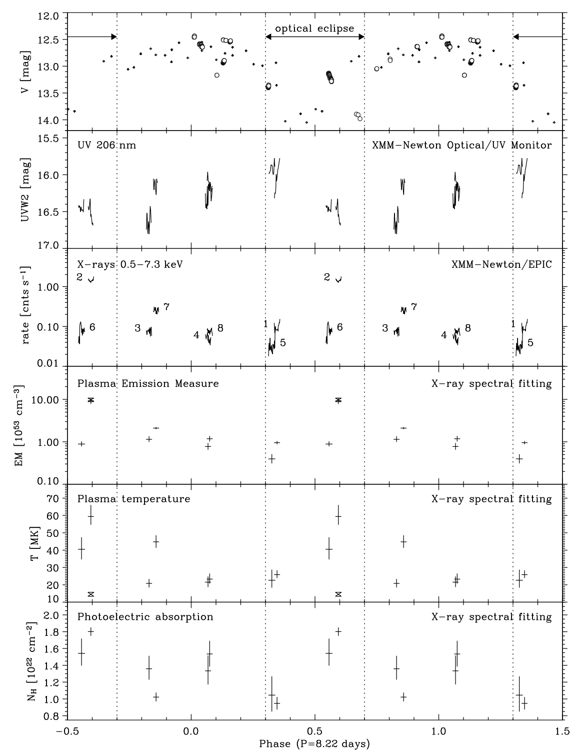

Figure 1: Light curves and plasma parameters of AA Tau folded in phase with the rotation period of 8.22 days. From top to bottom panel: the optical, UV, and X-ray light curves (XMM-Newton observations of February 2003 are labeled); the variations of the plasma emission measure(s) and temperature(s), and the photoelectric absorption. In the top panel, black dots show for comparison the optical ground monitoring of Aug.–Oct. 2003 (Bouvier et al. 2007). The arrow shows the eclipse phase based on the optical ground monitoring.

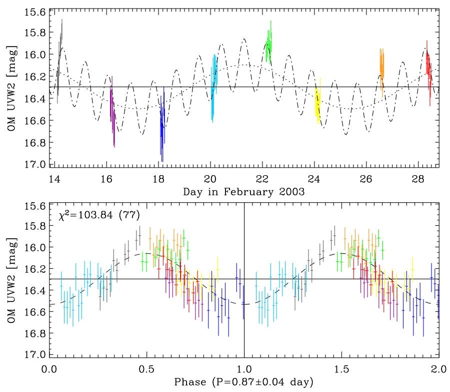

Figure 2: Weekly and daily UV variability of AA Tau observed with the XMM-Newton optical/UV monitor (OM). Top panel: the dotted and dashed-dotted line show the weekly UV modulation attributed to the optical eclipse period (8.22 days), and the overall UV modulation. The horizontal line shows the average flux. Bottom panel: the dashed line shows the daily UV modulation folded in phase after subtraction of the weekly modulation.

slow cooling of the magnetically confined plasma (e.g., Favata et al. 2005). X-ray flares with unusually long rise phases have also been reported (e.g., Grosso et al. 2004). A bright X-ray flare with a rapid ($\tau_{decay} \leq 0.6$ day) cooling phase can reproduce the large amplitude, and also the flatness of the light curve of AA Tau at its maximum. Moreover, the fitting of the X-ray spectra indicates low (23 MK) plasma temperature during the low activity levels; and a hot (60 MK) and cool (15 MK) plasma component, associated with an elevated level of X-ray surface flux, during observation #2, as this is observed in the most active T Tauri stars (Preibisch et al. 2005). We conclude that this high temperature and X-ray surface flux point to an enhanced X-ray activity produced by a large flare.

The OM simultaneously provided UV photometry (UVW2 filter at 206 nm) with a ∼15 min sampling rate (Fig. 2). The continuous monitoring with the OM central window is crucial to determine accurately the UV variations on hour timescale. We find that AA Tau is variable in UV by an amount of a few 0.1 mag on a few hours timescale, and up to 1 mag on a week timescale. There are no correlation between the UV and X-ray variations (Fig. 1). To model the UV variability, we first assume that the UV flux must be somehow modulated by the warped inner disk. The resulting fit is poor ($\chi^2 = 206.5$ for 80 d.o.f.), with large residuals mainly due to daily variations that cannot be properly fitted with this simple model. The fit is improved by adding a (high-frequency) modulation with a period of 0.9 day (Fig. 2). We cannot exclude a weird combination of several uncontroled parameters (e.g., sampling rates, UV monotonic increase/decrease, aliases,...), that could produce an artefact mimicking a periodic light curve. A longer UV observation with the OM is necessary to confirm this high-frequency period, which would suggest a non-steady accretion.

2 X-ray and UV variabilities versus rotational phase

We use the OM short exposure images, taken at the start of each science observation of XMM-Newton with the V filter for the identification of guide stars, to monitor AA Tau in optical. We also supplemented our XMM-Newton observations with an optical ground-based monitoring of AA Tau to secure the dates of the optical eclipses (top pannel of Fig.1). Half of the XMM-Newton observations were obtained during optical eclipses; in particular, observations #2 and #6 were close to the center of the optical eclipse. The UV flux was the highest just before the eclipse starts and the lowest towards the end of it. Indeed, the lowest UV flux was observed during the observation #3 at the end of the egress phase, i.e., outside the primary eclipse. The delay of 0.2 in phase between the optical and UV eclipses, and the smaller depth of the UV eclipse ($\Delta UVW2 \sim 0.4$ mag) compared to the optical eclipse ($\Delta V \sim 1.5$ mag), suggests a trailing accretion funnel flow, producing a strong absorption of the UV photons emitted at the accretion shock. No eclipses were detected in X-rays. The X-ray flare was observed close to the center of the optical eclipse. The fitting of the X-ray spectra indicates a variable (gas) column density, $N_H \sim (1.0$–$1.8) \times 10^{22}\,\mathrm{cm}^{-2}$; but similar N_H values are observed both during the eclipse and outside it. The maximum of N_H is measured during the X-ray flare, but increases of N_H were also reported during large stellar flares, and solar flares are sometimes associated with coronal mass ejection (see review by Güdel 2004). Therefore, we cannot rule out that the peak of N_H is due to this energetic event. The gas column density, derived from the photoelectric absorption of the X-rays emitted by the active corona of AA Tau, is 8–15 times larger than the value derived from the dust extinction ($A_V \sim 0.8$ mag). To explain this excess of gas column density, Schmitt & Robrade (2007) introduced an additional absorption in a disk wind or a peculiar dust grain distribution. We propose instead to identify this excess of (dust free) gas with the low density funnel flows, that blanket nearly the whole magnetosphere outside the narrow accretion funnel flows, loaded with higher density material (see three-dimensional MHD simulations of disk accretion to a rotating magnetized star; e.g., Romanova et al. 2003).

3 Conclusions

Our optical and X-ray monitoring of AA Tau show a lack of eclipses in X-rays, which indicates that X-ray emitting regions are located at high latitudes. A bright X-ray flare occured during the transit of an accretion funnel flow, which locates the active X-ray area likely close to the foot of the accretion funnel flow. We speculate that a magnetic interaction exists between the free falling accretion flow and the strong magnetic field of the stellar corona, which may trigger magnetic reconnections and give rise to bright flares, which boost the X-ray emission.

References

Bouvier, J., et al. 2007, A&A, 463, 1017
Favata, F., et al. 2005, ApJS, 160, 469
Grosso, N., et al. 2004, A&A, 419, 653
Güdel, M. 2004, A&A Rev., 12, 71
Preibisch, T., et al. 2005, ApJS, 160, 401
Romanova, M. M., et al. 2003, ApJ, 595, 1009
Schmitt, J. H. M. M. & Robrade, J. 2007, A&A, 462, L41