WAS AN OUTBURST OF AQUILA X-1 A MAGNETIC FLARE?

NOAM SOKER
Department of Physics, Technion–Israel Institute of Technology, Haifa 32000, Israel; soker@physics.technion.ac.il

Received 2010 June 3; accepted 2010 August 28; published 2010 September 13

ABSTRACT

I point to an interesting similarity in the radio and the soft X-ray light curves between the 2009 November outburst of the X-ray binary Aquila X-1 and some solar flares. The ratio of the soft X-ray and radio luminosities of Aquila X-1 in that outburst is also similar to some weak solar flares, as is the radio spectrum near 8 GHz. Based on these as well as on some other recent studies that point to some similar properties of accretion disk coronae and stellar flares, such as the ratio of radio to X-ray luminosities, I speculate that the soft X-ray outburst of Aquila X-1 was related to a huge magnetic flare from its disk corona.

Key words: stars: flare – X-rays: binaries

Online-only material: color figure

1. INTRODUCTION

In a recent paper, Miller-Jones et al. (2010, hereafter M2010) present a detailed study of an outburst of the X-ray binary (XRB) Aquila X-1 (Aql X-1). Aql X-1 is a binary system of a K7V star and a neutron star (NS) that experiences repeated outbursts. M2010 discuss the outburst properties in the context of the transition from the hard state to the soft state and back, and plot the evolution of Aql X-1 on the hardness–intensity diagram commonly used for outbursts of accreting black holes (BHs).

During the canonical hard state of a BH XRB outburst, a steady optically thick compact jet is expected. During the hard-to-soft state transition (and sometimes back the other way) a major radio flare, brighter than the compact jet, occurs, and optically thin jet ejecta are often observed or inferred to be launched when the "jet line" is crossed (e.g., Fender et al. 2009). It is still not known whether the compact jet exists during the soft state. M2010 notice two significant differences between the outburst of Aql X-1 and outbursts of BHs. These are the flat radio spectrum between 5 and 8 GHz, and the absence of bright, optically thin, relativistically moving knots. A major radio outburst is observed to occur during the hard–soft transition in the outburst of Aql X-1. However, during this transition, its spectrum is flat and no jet ejecta are seen. G2010 argue that during this transition only the compact jet is being observed. The presence of a compact jet in this transition may or may not be consistent with BH XRBs. It is the lack of transient, optically thin jet emission in this transition that is different from other BH XRB outbursts.

In light of these differences and some similarity with solar flares, I speculate on an alternative interpretation of the radio and soft X-ray emissions (but not of the hard X-ray emission preceding these two) based on magnetic flares. The alternative interpretation of magnetic activity was discussed for an accreting white dwarf by Soker & Vrtilek (2009). Soker & Vrtilek (2009) suggested that the radio emission from an outburst of the dwarf nova SS Cyg reported by K{"o}rding et al. (2008) originated from magnetic activity that formed a corona similar to coronae found in magnetically active stars, rather than from jets. Soker & Vrtilek (2009) based their claim on the results of Laor & Behar (2008, hereafter LB2008), who found that when the ratio between radio and X-ray fluxes of accretion disks in radio-quiet quasars is as in active stars, $L_r/L_x \lesssim 10^{-3}$, then most of the radio emission might come from coronae. In LB2008, the radio luminosity is $\nu L_{\nu}$, usually at around 6 cm, while $L_r$ is the integrated X-ray luminosity in the range 0.2–20 keV. Jets might still occur. If the magnetic activity in erupting accreting disks is similar to that in active stars, then mass ejection is expected. The presence of coronae above accretion disks (e.g., Galeev et al. 1979; Done & Osborne 1997; Wheatley & Mauche 2005) and the connection between coronae and jets (e.g., Fender et al. 1999; Markoff et al. 2005; Rodriguez & Prat 2008) have already been proposed. However, the results of Ishida et al. (2009; also LB2008) put the presence of coronae in accretion disks on a solid ground and further suggest that magnetic activity similar to that in active stars occurs in these coronae.

The speculative interpretation in the present Letter (Section 2) is based on three properties of the 2009 November outburst of Aql X-1 (M2010). I emphasize that I do not propose an alternative explanation of the hard (> 15 keV) X-ray peak, and in any case postpone its detailed study for a future paper. In X-ray transients, the hard X-ray peak can generally be accounted for by a disk instability as studied by Dubus et al. (2001). In the present case, the hard X-ray peak has a triangular shape (see definition in Chen et al. 1997) for ~12 days. The radio peak appears during the decay phase of the hard X-ray emission. The soft (Rossi X-Ray Timing Explorer/All-Sky Monitor; 2–10 keV) X-ray emission appears with the hard X-ray emission, but its large and rapid rise starts only after the radio peak (see below). The two peaks, one in the hard X-ray followed by one in the soft X-ray, can be seen for another flare of Aql X-1 in Yu et al. (2003), but they do not have radio observations. The two X-ray peaks do not resemble at all the secondary peaks discussed for X-ray novae by Chen et al. (1997) and must be explained by a different process. Among XRB systems, the double peak structure of the outburst is common, like XTE J1859+226 (Brocksopp et al. 2002) in which the radio peak occurs at the start of the extended soft X-ray peak; the hard X-ray peak occurs before the peaks of the radio and soft X-ray emissions (Brocksopp et al. 2002). Such a structure is seen in solar flares as well. In the magnetic flare model, the hard X-ray peak is related to the event that rapidly amplifies the magnetic field. This field later powers the radio and soft X-ray emissions.

The appearance of the hard X-ray and soft X-ray peaks one after the other is quite similar to that seen in BH XRB systems,
but it is not at all similar to the delay in rise to maximum between the optical and extreme UV and X-ray emissions in dwarf novae (Mauche et al. 2001; Wheatley et al. 2003). In Aql X-1, the two peaks are separated, while in dwarf novae their behavior with time is more or less similar, with a relatively short delay. The disk instability can account for the delay in dwarf novae (Schreiber et al. 2003), but here a different explanation is required.

2. THE MAGNETIC FLARE INTERPRETATION

2.1. Light Curves

Many solar flares, as well as of similar stars such as UV Ceti (Güdel et al. 1996), show the Neupert effect (Neupert 1968). This effect is a behavior where the integration of the radio flux (and in many cases the non-thermal hard X-ray emission) is proportional to the X-ray flux at rise. In some cases, the radio peak comes at the beginning of the X-ray rise.

In Figure 1, I compare the behavior of one specific solar flare as compiled by Güdel et al. (1996; more detail in Cliver et al. 1986; Dennis & Zarro 1993; and Benz & Güdel 1994) with the 2009 November outburst of Aql X-1 (M2010) in radio and soft X-ray emissions. The solar flare is a gradual hard X-ray burst (GHB) of 1981 April 26 (Cliver et al. 1986). In many cases, GHBs are preceded by coronal mass ejection and with a hard X-ray peak. The flux units are in relative units, while each time unit is 1 hr for the solar flare and 7.1 weeks for Aql X-1. Namely, a ratio of 170 in the timescale. Radio fluxes are in thin lines and X-ray fluxes are in thick lines. Aql X-1 is depicted by a blue dashed line while the solar flare is shown with a red solid line. Note that the Aql X-1 radio intensity was multiplied by 600, as the ratio $L_r/L_x \sim 600$ times weaker in Aql X-1 as in the solar flare that is shown.

I note the following similarities between the bursts in these two vastly different systems:

1. The general shape of the radio (3.6 cm–6 cm) and soft X-ray emissions $L_r/L_x \sim 10^{-5}$ that holds over 20 orders of magnitude, excluding some systems, e.g., the Sun, Galactic BH XRBs, and radio-loud quasars. In some cases, this ratio is as low as $\sim 10^{-8}$, in particular in weak solar flares (microflares; Benz & Güdel 1994) and in Galactic BH XRBs. LB2008 raised the possibility that the lower $L_r/L_x$ in BH XRBs is due to the higher temperature of their disk. If this is indeed the case, it strengthens the connection between the flaring systems proposed here.

2.2. Fluxes Ratio

LB2008 present a correlation between the radio and soft X-ray luminosities $L_r/L_x \sim 10^{-5}$ that holds over 20 orders of magnitude, excluding some systems, e.g., the Sun, Galactic BH XRBs, and radio-loud quasars. In some cases, this ratio is as low as $\sim 10^{-8}$, in particular in weak solar flares (microflares; Benz & Güdel 1994) and in Galactic BH XRBs. LB2008 raised the possibility that the lower $L_r/L_x$ in BH XRBs is due to the higher temperature of their disk. If this is indeed the case, it strengthens the connection between the flaring systems proposed here.
In the 2009 November outburst of Aql X-1 this ratio was $(L_r/\nu_{\text{peak}})/(L_x/\nu_{\text{peak}}) \simeq 10^{-8}$. At the radio peak, the X-ray luminosity was lower and this ratio was $\sim 3 \times 10^{-8}$. This is similar to weak solar flares. In the solar flare from 1981 April 26 this ratio is $L_r/\nu_{\text{peak}} \sim 10^{-5}$ (the total energy in the radio is six orders of magnitude below that in the X-ray). We note that the ratio in solar flares is mainly obtained with the soft X-ray flux $0.5-2$ keV (e.g., Güdel et al. 1996). Taking the $0.1-20$ keV range for the solar flare will reduce the $L_r/\nu_{\text{peak}}$ ratio only by a factor of two. The fluxes for Aql X-1 is taken for the $2-16$ keV band (M2010), which is somewhat narrower than the band used by LB2008 ($0.2-20$ keV). For the spectra of these sources this does not make a significant difference, as emission peaks around a few keV.

In accretion onto compact objects some X-ray emission comes from shocked gas, a process that does not exist in the Sun. Over all, the ratio $L_r/L_x \simeq 10^{-5}$ in the 2009 November outburst of Aql X-1 falls within the range of weak solar flares and BH XRBs too.

**2.3. Flat Radio Flux**

M2010 attribute the flat radio spectrum to an optically thick compact jet. However, in BH XRB outbursts, the radio emission after a major radio flare is dominated by optically thin jet ejecta, and there is currently no evidence that the compact jet remains on. For the 2009 November outburst M2010 find (near 8 GHz) $S_{\nu}(\text{radio}) \propto \nu^{0.20 \pm 0.01}$. The weighted Very Large Array data yield $S_{\nu}(\text{radio}) \propto \nu^{0.5 \pm 0.01}$. Both measurements would need to be off by $3\sigma$ to be consistent with $\nu^{-0.5}$ (as in optically thin jet ejecta). According to M2010, this is not compatible with internal shocks in jets. It thus seems that a magnetic flare can account for this radio spectrum. Kundu et al. (2009), for example, find for the magnetic loop top in a solar flare $S_{\nu}(\text{radio}) \propto \nu^{-0.5}$ near 8 GHz.

Although XRB systems might show different behaviors (e.g., Agrawal & Misra 2009), in general, XRB emission can be well fitted by a combination of a soft component composed of a multicolor disk blackbody and a hard component of a power law or Comptonized single temperature (e.g., Maitra & Bailyn 2004; Gou et al. 2009). Stellar (including solar) flares can be fitted by emission from thin plasma (coronal emission), e.g., Battaglia et al. (2009). The X-ray spectra of stellar flares, therefore, are not similar to those of XRB systems. But they do not need to be identical in the proposed model. LB2008 note the different X-ray spectra of active galactic nuclei (AGNs) and stellar flares. They argue that the cooling mechanism of the hot gas formed by the magnetic activity is different. While in stellar flares the cooling is by thermal emission from optically thin plasma, in AGNs the cooling is Comptonization of the optical-UV disk continuum by hot thermal gas ($T \gtrsim 10^{6}$ K). Still, LB2008 argue, in both types of systems the hot plasma is formed by magnetic activity.

As for XRB systems discussed here, it is possible that the hot gas is cooling by heating the disk. For example, the hot electrons formed in the magnetic reconnection process stream down along magnetic field lines anchored to the disk. This will increase the blackbody emission from the disk. In addition, some contribution from optically thin plasma (as in stellar flares) is expected. These processes are the subject of a future paper. In particular, two processes will be studied: the formation of the very hot gas by magnetic activity in the flaring region, and heat conduction from that region to the disk. After all, this chain of events is what is behind the Neupert effect: hot electrons heat (and evaporate) the chromosphere. This future study will have to examine where the heat conduction in the environment of accretion disks can indeed heat the disk to increase its blackbody radiation.

**3. DISCUSSION AND SUMMARY**

The three properties discussed in Section 2 hint that the behavior of the soft X-ray and radio emissions in the 2009 November outburst of the XRB Aql X-1, were similar to GHBs in the Sun and similar stars, e.g., UV Ceti (Güdel et al. 1996). The strongest of these properties is the similar light curve in hard X-ray, soft X-ray, and radio emissions. The similarity in the radio and soft X-ray light curves is shown in Figure 1. The hard X-ray peak in Aql X-1 can be attributed to the disk instability (Dubus et al. 2001). It is the behavior of the soft X-ray and radio emissions that I try to explain in this Letter.

The typical size of the soft X-ray loop of solar GHBs is $\sim 0.04 R_\odot$ (see Figure 10 in Cliver et al. 1986). If we use a very simple scaling from the solar flare, the duration of the Aql X-1, which is $\sim 170$ times as long as a solar flare, implies a reconnection size that is $\sim 170$ times larger, or $D_{\text{rec}} \sim 7 R_\odot$. Interestingly, the orbital separation in Aql X-1 is $4.5 R_\odot$; for an orbital period of 19 hr (Chevalier & Ilovaisky 1991) and a total mass of $2 M_\odot$ (Welsh et al. 2000). Namely, the magnetic field reconnection event occurs over a size about equal to the binary separation, which is just a little larger than the disk size.

I propose that a disk instability triggered the formation of an extended corona around the accretion disk, on a size about equal to the binary separation. This is the event seen in the hard X-ray of Aql X-1 by M2010 that preceded both the radio and soft X-ray fluxes. Then, a major magnetic flaring (reconnection and other means of magnetic energy release) occurred. Such a magnetic flare can accelerate gas and lead to the formation of a jet.

The total energy emitted in the soft X-ray in the flare is $\sim 10^{35}$ erg. Taking the total volume occupied by the reconnecting magnetic fields to be $V = (4 R_\odot)^2$, the required average magnetic field intensity is $B \simeq 10^3$ G. This is not unreasonable. Active stars with a similar size of $\sim R_\odot$ have magnetic fields of $\sim 10^5$ G. The magnetic field of the Ap star HD 137509, for example, reaches the value of 37,000 G (Mathys 1995). The magnetic field comes from a disk dynamo, which should be a major issue to be studied in the future.

Encouraging are also some similarities of the properties mentioned in this Letter to strong and long X-ray flares of young stars characterized by having active or inactive accretion disks around them. Favata et al. (2005) observed the Orion Nebula cluster with Chandra, and analyzed flares from young stars with such disks around them. Some flares last for up to 5 days. The structure Favata et al. (2005) infer is of large and long, $\sim 10^{12}$ cm = $14 R_\odot$, magnetic structures. A large and long magnetic loop can be behind the outburst of Aql X-1 in the proposed model. The total energy in the strong flares studied by Favata et al. (2005) is $\sim 10^{37}$ erg. This is $\sim 10^{-6}$ times that in the flare of Aql X-1. The six (out of 32) brightest flares have luminosities in the range of $L_x = (1.6-7.8) \times 10^{32}$ erg s$^{-1}$, or $\sim 10^{-5}$ times that of the outburst of Aql X-1. This ratio is of the same order of magnitude as the ratio of the gravitational potential wells in the two types of objects.

Some points must be clarified before the speculative interpretation suggested here can gain more credibility. (1) It should be shown that a reconnection event (or several events) can account for the high luminosity in the X-ray (up to $\sim 0.1 L_{\text{edd}}$). (2) There is a need to compare not only the observed properties, but also the physical processes. Namely, much work has been done on
solar flares and GHBs. It will have to be shown that similar processes can take place in an extended corona of XRBs.

The proposed magnetic flare explanation is a paradigm shift from the common interpretation of outburst in XRBs. This paradigm shift can be traced back to LB2008 who pointed out the similar radio-to-X-ray flux ratio in a variety of astronomical objects, including stellar flares and accreting super massive BHs in AGNs. I therefore suggest that the proposed magnetic flaring model holds for BH XRBs as well (see also, e.g., Rodriguez & Prat 2008). Basically, where we expect strong dynamo to operate, we should expect strong magnetic flares. Accretion disks have very strong shear compared with stars and they must have some kind of turbulence to supply the viscosity. As such, a strong dynamo exists in accretion disks. The large flares are expected to occur when the magnetic field energy is further amplified. Such can be the case when the disk becomes unstable and erupt. The outflowing gas stretches magnetic field lines and substantially amplifies the field. After this triggering eruption, the field lines reconnect and release the huge amount of magnetic energy. However, in some cases, disk outbursts might not result in substantial magnetic field amplification, and no large magnetic flare will occur.

If the similarity presented in this paper holds, it adds to previous suggestions on similarity between coronae in active stars and accretion disks (LB2008), and similarity in the processes of mass ejection by solar flares and the launching of jets from accretion disks powered by magnetic fields reconnection (de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino et al. 2010; Soker 2007).

I thank two anonymous referees for very helpful comments. This research was supported by the Asher Fund for Space Research at the Technion and the Israel Science foundation.

REFERENCES

Agrawal, V. K., & Misra, R. 2009, MNRAS, 398, 1352
Battaglia, M., Fletcher, L., & Benz, A. O. 2009, A&A, 498, 891

Benz, A. O., & Güdel, M. 1994, A&A, 285, 621
Brocksopp, C., et al. 2002, MNRAS, 331, 765
Chen, W., Shrade, C. R., & Livio, M. 1997, ApJ, 491, 312
Chevalier, C., & Ilovaisky, S. A. 1991, A&A, 251, L11
Cliver, E. W., Dennis, B. R., Kiplinger, A. L., Kane, S. R., Neidig, D. F., Sheeley, N. R., Jr., & Koomen, M. J. 1986, ApJ, 305, 920
de Gouveia Dal Pino, E. M., & Lazarian, A. 2005, A&A, 441, 845
de Gouveia Dal Pino, E. M., Piovezan, P. P., & Kadowaki, L. H. S. 2010, A&A, 518, A5
Dennis, B. R., & Zarro, D. M. 1993, Sol. Phys., 146, 177
Done, C., & Osborne, J. P. 1997, MNRAS, 289, 649
Dubus, G., Hameury, J.-M., & Lasota, J.-P. 2001, A&A, 373, 251
Favata, F., Flaccomio, E., Reale, F., Micela, G., Scintino, S., Shang, H., Stassun, K. G., & Feigelson, E. D. 2005, ApJS, 160, 469
Fender, R., et al. 1999, ApJ, 519, L165
Fender, R. P., Homan, J., & Belloni, T. M. 2009, MNRAS, 396, 1370
Galeev, A. R., Osipov, R., & Vaijana, G. S. 1979, ApJ, 229, 318
Gou, L., et al. 2009, ApJ, 701, 1076
Güdel, M., Benz, A. O., Schmitt, J. H. M. M., & Skinner, S. L. 1996, ApJ, 471, 1002
Ishida, M., Okada, S., Hayashi, T., Nakamura, R., Terada, Y., Mukai, K., & Hamaguchi, K. 2009, PASJ, 61, 77
Körding, E., Rupen, M., Knigge, C., Fender, R., Dhawan, V., Templeton, M., & Maxlow, T. 2008, Science, 320, 1518
Kunda, M. R., Grechnev, V. V., White, S. M., Schmahl, E. J., Meshalkina, N. S., & Kashapova, L. K. 2009, Sol. Phys., 260, 135
Laor, A., & Behar, E. 2008, MNRAS, 390, 847 (LB2008)
Maitra, D., & Bailyn, C. D. 2004, ApJ, 608, 444
Markoff, S., Nowak, M. A., & Wilms, J. 2005, ApJ, 635, 1203
Mathys, G. 1995, A&A, 293, 746
Mauche, C. W., Mattei, J. A., & Bateson, F. M. 2001, in ASP Conf. Ser. 229, Evolution of Binary and Multiple Star Systems, ed. Ph. Podsiadlowski et al. (San Francisco, CA: ASP), 367
Miller-Jones, J. C. A., et al. 2010, ApJ, 716, L109 (M2010)
Neupert, W. M. 1968, ApJ, 153, L59
Rodriguez, J., & Prat, L. 2008, arXiv:0811.3519
Schreiber, M. R., Hameury, J.-M., & Lasota, J.-P. 2003, A&A, 410, 239
Soker, N. 2007, in IAU Symp. 243, Star–Disk Interaction in Young Stars, ed. J. Bouvier (Cambridge: Cambridge Univ. Press), 195
Soker, N., & Vrtilek, S. D. 2009, arXiv:0904.0681
Welsh, W. F., Robinson, E. L., & Young, P. 2000, AJ, 120, 943
Wheatley, P. J., & Mauche, C. W. 2005, in ASP Conf. Ser. 330, The Astrophysics of Cataclysmic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota (San Francisco, CA: ASP), 257
Wheatley, P. J., Mauche, C. W., & Mattei, J. A. 2003, MNRAS, 345, 49
Yu, W., Klein-Wolt, M., Fender, R., & van der Klis, M. 2003, ApJ, 589, L33