X-RAY ACTIVITY PHASED WITH PLANET MOTION IN HD 189733?

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ABSTRACT

We report on the follow-up XMM-Newton observation of the planet-hosting star HD 189733 we obtained in 2011 April. We observe a flare just after the secondary transit of the hot Jupiter. This event shares the same phase and many of the characteristics of the flare we observed in 2009. We suggest that a systematic interaction between planet and stellar magnetic fields when the planet passes close to active regions on the star can lead to periodic variability phased with planetary motion. By means of high-resolution X-ray spectroscopy with the Reflection Grating Spectrometer on board XMM-Newton, we determine that the corona of this star is unusually dense.

Key words: planetary systems -- stars: activity -- stars: coronae -- stars: individual (HD189733) -- X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The evidence of star–planet interaction (SPI) in the X-ray band is a lively matter of debate. To first order, close-in giant planets (also known as “hot Jupiters”) should affect their host stars through both tidal and magnetohydrodynamical effects (cf. Cuntz et al. 2000; Ip et al. 2004). Both effects should scale as the $-3$ power distance between the bodies (Saar et al. 2004). Kashyap et al. (2008) showed that stars with hot Jupiters are statistically brighter in X-rays than stars without hot Jupiters. On average Kashyap et al. (2008) observed an excess of X-ray emission by a factor of four in the hot Jupiter sample. Interplay between the magnetic fields of the hot Jupiter and the star may be the source of this difference. This could be due to interacting winds and magnetic fields or indirectly by enhancing the stellar dynamo. On the other hand, Poppenhaeger et al. (2010; and Poppenhaeger & Schmitt 2011) have found no statistical evidence of X-ray SPI as claimed by Kashyap et al. (2008).

The system of HD 189733 offers a unique environment to study SPI effects in X-rays and disentangle them from proper coronal activity. It is composed of a K1.5V type star (at only 19.3 pc from Sun), and an M4 companion at 3200 AU from the primary, orbiting on a plane perpendicular to the line of sight. It hosts a hot Jupiter class planet (HD 189733 b) at a distance of only 0.031 AU with an orbital period of $\sim 2.22$ days (Bouchy et al. 2005).

In 2009, we observed the eclipse of the planetary companion to HD 189733 with the goal of studying SPIs in the case of a hot Jupiter (Pillitteri et al. 2010, hereafter Paper I). We observed a softening of the spectrum in strict correspondence with the planetary eclipse, and a flare which occurred 3 ks after the end of the eclipse of the planet. The non-detection of the M-type companion is a strong constraint on the age of the system at $\geq 1.5–2$ Gyr.

The high age of the secondary is interesting because it is inconsistent with age of the system as derived from stellar activity which is of order 600 Myr (Melo et al. 2006). Recently, Schrör et al. (2011) reported on Chandra observations of a planetary transit of Corot 2A, finding a similar case. While they do not detect the transit in X-rays, they find that the primary is X-ray-bright with a luminosity $\sim 1.9 \times 10^{29}$ erg s$^{-1}$, indicating an age $< 300$ Myr. Meanwhile, a potential stellar companion was undetected down to a limit of $L_X \approx 9 \times 10^{26}$ erg s$^{-1}$ which is inconsistent with the 300 Myr age and the distance of 270 pc.

The beginning of the flare observed in 2009 in HD 189733 is at phase $\phi \sim 0.54$, which coincides with a location 77$^\circ$ forward of the sub-planetary point and emerging to the day side of the star. This is almost exactly the location of the magnetic sub-planetary point as calculated by Lanza (2008). The flare could be associated with the emergence of the footpoint of the magnetic column to the earth-facing side or a complex active region induced by magnetic SPI. Overall, the flare is associated with a change of the mean plasma temperature from $\sim 0.5$ keV to $\sim 0.8$ keV. The O vii triplet is in excess with respect to the best-fit model. In the RGS (Reflection Grating Spectrometer on board XMM-Newton) spectra we observed that during the flare the inter-combination line seems to disappear and the forbidden line is less luminous.

In this Letter, we report on the follow-up observation obtained in 2011 April at the same phase as in 2009, during an eclipse of the planet. Sections 2 and 3 describe the observation and the results. Section 4 reports our conclusions.

2. OBSERVATION AND DATA ANALYSIS

The observational setup mimics our previous observation made on 2009 May 18. We obtained an X-ray observation with XMM-Newton around the eclipse of the planet of HD 189733 on 2011 April 30, starting at 23:14.20 (ObsID: 0672390201), and for a total duration of $\sim 39.1$ ks. As in the previous observation, we used the Medium filter. The time between observations of HD 189733 was almost two years or exactly 61530.1 ks (mid-eclipse to mid-eclipse). The period of the star is 11.953 $\pm$ 0.045 periods, while the planet had orbited it $\sim 39.1$ ks. As in the previous observation, we used the Medium filter. The time between observations of HD 189733 was almost two years or exactly 61530.1 ks (mid-eclipse to mid-eclipse). The period of the star is 11.953 $\pm$ 0.009 days (Henry & Winn 2008), hence the star had rotated through 59.5795 $\pm$ 0.045 periods, while the planet had orbited it 321 times.

For the reduction of the data we followed the same procedure as in Paper I, by using SAS ver. 11.0 to extract events, light curves, and spectra of HD 189733 recorded with EPIC camera and RGS. To fit the spectra, we used 2-T VAPEC models for the pre-flare phases (see description of the light curve in Section 3.1) with different temperatures but coupled to have the same abundances. Abundances of Fe, Ne, and O were left free to vary while all other abundances were kept fixed at the solar values. For the flare and post-flare phases we added a...
third VAPEC component keeping frozen the parameters of the first two VAPEC components. The abundances of the third component were linked and fixed. We obtained estimates of the temperature and emission measure of the flaring plasma, also following its fading after the flare. We applied the same procedure of best fit to the spectra obtained in 2007 (for the whole observation) and 2009 (split in pre-flare, flare, and post-flare phases) in order to compare the results.

We merged the RGS spectra in the non-flare and in the flare state of all observations. Flare and non-flare states were fitted independently using Gaussian lines with a narrow intrinsic line width in the SHERPA fitting tool (Refsdal et al. 2011), so that the total line width is dominated by instrumental broadening. Lines are adjusted in wavelength to account for possible errors in the zero point of the wavelength calibration, but the wavelength difference in multiplets is held constant. Within the errors, all wavelengths are compatible with the theoretical values. Instrumental background and source continuum are assumed to be constant over a small wavelength region around the fitted lines. The fits are done using a Cash statistic, which takes into account the Poisson distribution of counts, but the estimates of errors might be uncertain for very low count numbers.

3. RESULTS

3.1. PN Light Curve and Spectra

Figure 1 shows the light curve of EPIC PN in 0.3–1.5 keV. The 2009 light curve (dotted line) is shown in phase with the 2011 light curve. Phase is marked on the top axis. The time bins are 400 s. Bottom panel: median of energy (PI) as a function of time. The error bar of $\langle PI \rangle$ curve is about 12–15 eV. Vertical lines mark first contact to fourth contact. Light curves of $\langle PI \rangle$ are smoothed by taking the median of the sample of 200 events and varying the sample by adding five new events and removing the five oldest ones (cf. Paper I).

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

Figure 1. Top panel: light curve of PN in 0.3–1.5 keV. The 2009 light curve (dotted line) is shown in phase with the 2011 light curve. Phase is marked on the top axis. The time bins are 400 s. Bottom panel: median of energy (PI) as a function of time. The error bar of $\langle PI \rangle$ curve is about 12–15 eV. Vertical lines mark first contact to fourth contact. Light curves of $\langle PI \rangle$ are smoothed by taking the median of the sample of 200 events and varying the sample by adding five new events and removing the five oldest ones (cf. Paper I).

The overall rate in 2011 is similar to the PN rate recorded in 2009 and about twice the PN rate in the 2007 observation (quiescent rate in 2009 and 2011: $\sim 100 \pm 12$ ct ks$^{-1}$; quiescent rate in 2007: $\sim 60 \pm 10$ ct ks$^{-1}$). The average energy of the spectrum in 2011 before and during the eclipse is 675 ± 20 eV; it was 700 ± 10 eV in 2009 before the eclipse and 660 ± 10 eV during the eclipse. During the planetary eclipse we do not see the softening as in 2009.

The most striking feature is the flare after the end of the planetary eclipse, which is analogous to the main flare seen in the 2009 observation. In 2011, the flare starts at phase 0.52, while it starts at 0.54 in 2009. The duration of the flare ($\sim 7$ ks, evaluated by eye), the peak rate ($\sim 230$ ct ks$^{-1}$ versus $\sim 210$ ks$^{-1}$ in 2009), and the presence of secondary impulses during the decay are quite similar to those observed in 2009 as well. The detection of two flares within 120 ks (i.e., the sum of exposure times in 2007, 2009, and 2011 observations) is interesting on its own, given that for active stars the typical rate of occurrence of bright flares is one every 500 ks (Wolk et al. 2005; Caramazza et al. 2007).

Table 1 reports the best-fit values of the spectra before, during, and after this flare. For comparison, we also report the values obtained with the same best fit scheme for the 2007 and 2009 observations. Figure 2 shows the PN spectra accumulated before, during, and after the bright flare observed in 2011.

The pre-flare phase has a best fit with two thermal components, at 0.24 keV and 0.73 keV, respectively. In 2009, the values are lower (0.18 keV and 0.47 keV, respectively) and thus the corona appears colder than in 2011.
During the flare the plasma has a marginally higher temperature, around 0.9 keV (flare temperature in 2009 was ∼1 keV). In fact, the flare spectrum shows an excess around 0.9 keV (Figure 2).

In the post-flare phase the plasma cools essentially to the pre-flare temperature. The third component has a temperature similar to the hot component of the pre-flare and it is almost indistinguishable from the latter. It is worth noting that the luminosity of the star remains slightly higher after the flare. This is observed in both 2011 and 2009.

As suggested in Paper I, this flare could arise from an active region which sits in a well-defined location on the stellar surface. It is plausible that in this region a strong magnetic field is present given its configuration. The periodic passage of the planet could trigger magnetic reconnections and thus strong flares that could not arise elsewhere on the stellar surface. Fares et al. (2010) have published maps of the configuration of the magnetic field of HD 189733 in 2006–2008. The field has a complex configuration with a toroidal component up to 40 G in 2008 (the closest to the 2009 observation and the present one) and it changed configuration between 2006 and 2008. The dipolar component is strongly non-axisymmetric in 2008. Cohen et al. (2011) have shown through MHD simulations based on these maps that magnetic SPI is possible whenever the planetary and stellar Alfvénic surfaces intersect each other. Given the non-symmetric shape of the stellar magnetic field, the interaction of planetary and stellar fields does not occur continuously but at some phase determined by the planetary motion and the stellar rotation.

The emission levels in X-rays in 2009 and 2011 are quite similar. On the other hand, these are 80% greater than in 2007. This last one is the only line which is significantly detected by the RGS detectors; the line fluxes are compatible within the statistical errors. Due to CCD failures,

Table 1

| Phase     | \(kT_1\) (keV) | \(kT_2\) (keV) | \(kT_3\) (keV) | E.M.1 \((\text{cm}^{-3})\) | E.M.2 \((\text{cm}^{-3})\) | E.M.3 \((\text{cm}^{-3})\) | log \(f_X\) \((\text{erg s}^{-1} \text{cm}^{-2})\) | log \(L_X\) \((\text{erg s}^{-1})\) |
|-----------|----------------|----------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 2011 Pre  | 0.24\(^{+0.02}_{-0.03}\) | 0.75\(^{+0.08}_{-0.11}\) | \ldots | 5.8\(^{+1.0}_{-1.0}\) | 3.6\(^{+0.9}_{-0.9}\) | \ldots | \ldots | 28.17 |
| Flare     | (0.24) | (0.73) | 0.9\(^{+0.1}_{-0.1}\) | (5.8) | (3.6) | 3.0\(^{+0.5}_{-0.5}\) | \ldots | 28.29 |
| Post      | (0.24) | (0.73) | \ldots | (5.8) | (3.6) | 1.35\(^{+0.03}_{-0.15}\) | \ldots | 28.24 |
| 2009 Pre  | 0.18\(^{+0.08}_{-0.08}\) | 0.47\(^{+0.08}_{-0.08}\) | \ldots | 4.1\(^{+1.8}_{-1.8}\) | 5.6\(^{+2.3}_{-2.2}\) | \ldots | 28.15 |
| Flare     | (0.18) | (0.47) | 0.99\(^{+0.08}_{-0.08}\) | (4.1) | (5.6) | 3.2\(^{+0.4}_{-0.5}\) | \ldots | 28.29 |
| Post      | (0.18) | (0.47) | 0.62\(^{+0.2}_{-0.17}\) | (4.1) | (5.6) | 1.3\(^{+0.4}_{-0.3}\) | \ldots | 28.22 |
| 2007      | 0.24\(^{+0.01}_{-0.01}\) | 0.71\(^{+0.04}_{-0.03}\) | \ldots | 4.7\(^{+0.4}_{-0.3}\) | 2.8\(^{+0.3}_{-0.3}\) | \ldots | 28.05 |

Notes. We also report the fit of the 2007 observation with two 2-T VAPEC components. The abundances of Fe, Ne, and O in 2011 are derived from the pre-flare phase, with values: Fe = 0.57\(^{+0.11}_{-0.15}\), O = 0.51\(^{+0.09}_{-0.07}\), and Ne = 0.3\(^{+0.07}_{-0.03}\), respectively. The values of emission measures are given in units of \(10^{50} \text{ cm}^{-3}\).
O vii is visible only in RGS1, while Ne ix is visible only in RGS2.

3.2.1. Temperature

In the flares, the Ne x emission increases by about a factor of three in agreement with the increased temperature seen in the light curve of median energy and spectra of PN. The total emission of the He-like triplets is similar in flare and non-flare intervals.

The ratio of lines from different ionization stages can be used as a temperature diagnostic (Mewe 1991). Figure 3 shows the ratio of O viii/O vii emission compared to the total oxygen luminosity in these lines. Blue squares show main-sequence (MS) stars from the sample of Ness et al. (2004), and red triangles are classical T Tauri stars (CTTs), which are accreting pre-MS (PMS) stars (Robrade & Schmitt 2007; Günther 2011). CTTs show an excess of cool emission, which is likely powered by accretion shocks. HD 189733 is among the stars in the sample with the lowest X-ray luminosity and O viii/O vii ratio. Thus, it is marginally cooler than MS stars of comparable luminosity, but its corona is overdense like PMS accreting stars. All CTTs in Figure 3 are significantly brighter than HD 189733, but this is a selection bias because only the brightest CTTs can be observed with X-ray gratings.

3.2.2. Density

The ratio of the forbidden line f and the inter-combination line i in the He-like triplets is density sensitive (Mewe 1991; Porquet & Dubau 2000). In the low-density limit f/i is 3.5 for O vii (log n_e < 9) and 3.2 for Ne ix (log n_e < 10) according to the CHIANTI database (Dere et al. 1997, 2009). We performed Monte Carlo simulations to account for the non-Gaussian errors in the distribution (Günther & Schmitt 2009, Appendix A). The Ne ix lines are compatible with the low to moderate density limit in the non-flare state (95% confidence limit f/i > 2.2, i.e., log n_e < 11); in the flare spectrum the error is too large to constrain the density. The non-detection of the O vii i line in the flare is consistent with moderate densities; the 95% confidence lower limit is f/i = 0.5 (log n_e < 11.2). In the non-flare state, the 95% confidence upper and lower boundaries on the f/i ratio are 1.8 (log n_e > 10.5) and 0.6 (log n_e < 11.1). Generally, the coronal emission in MS stars is in the low-density limit (Ness et al. 2004), and only in a few bright flares have higher densities been seen (e.g., on Proxima Cen; Guédel et al. 2002, 2004).

The total luminosity in the He-like triplets changes little between the flare and the non-flare state. This could indicate that they originate in a dense region which is not affected by flare heating. However, the tentative change in the f/i ratio can be interpreted as a change in density, where the hotter plasma seen in the flare state has a lower density than in the non-flare state.

4. CONCLUSIONS

We have analyzed an XMM-Newton observation of HD 189733 at the secondary transit of the planet. We observed a flare with characteristics very similar to that observed in the previous observation at the same phase. The recurrence of such flares is explained by the following scenario: an active region is present at the same location on the stellar surface in both observations. The magnetic interaction with the planet is inducing a flaring activity in this region. The occurrence depends on the configuration of the stellar magnetic field and its strength. Further observations at the same phase can prove or reject this hypothesis.

High-resolution spectroscopy in quiescent and flaring states shows that the corona of HD 189733 is marginally cooler than MS stars with same oxygen line luminosity. We find a marginal change in the f/i ratio of O vii lines in the flare state, implying a lower density during flares with respect to quiescent state. In summary, the corona of HD 189733 stands apart with respect to other coronae of MS stars without hot Jupiters. It is cold like the solar corona but it is dense and 10 times more luminous and active. This could be related to SPI effects but more observations are needed to clarify the influence of its hot Jupiter on the corona.

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Facility: XMM

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