The corona of GJ 1151 in the context of star-planet interaction

G. Foster1,2*, K. Poppenhaeger1,2, J. D. Alvarado-Gómez1 and J.H.M.M. Schmitt3

1 Leibniz Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
2 Universität Potsdam, Institut für Physik und Astronomie, Karl-Liebknecht-Straße 24/25, 14476 Potsdam, Germany
3 Universität Hamburg, Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany

Accepted 2020 July 2. Received 2020 June 29; in original form 2020 May 11

ABSTRACT

The low-mass star GJ 1151 has been reported to display variable low-frequency radio emission, which has been interpreted as a signpost of coronal star-planet interactions with an unseen exoplanet. Here we report the first X-ray detection of GJ 1151’s corona based on XMM-Newton data. We find that the star displays a small flare during the X-ray observation. Averaged over the observation, we detect the star with a low coronal temperature of 1.6 MK and an X-ray luminosity of $L_X = 5.5 \times 10^{26} \text{erg/s}$. During the quiescent time periods excluding the flare, the star remains undetected with an upper limit of $L_{X,\text{qui}} \leq 3.7 \times 10^{26} \text{erg/s}$. This is compatible with the coronal assumptions used in a recently published model for a star-planet interaction origin of the observed radio signals from this star.

Key words: planet-star interactions – stars: coronae – X-rays: individual: GJ 1151

1 INTRODUCTION

Star-planet interactions are suspected to be able to alter stellar magnetic activity in a variety of ways. Tidal interaction may influence the rotational evolution and therefore the magnetic activity level of a host star, similar to tidal synchronization in close stellar binaries, or may influence convection in the outer layers of the star (Cuntz et al. 2000; Pont 2009; Pillitteri et al. 2014). Magnetic interaction is thought to be able to manifest itself through processes like reconnection of stellar and planetary field lines (Cuntz et al. 2000; Shkolnik et al. 2005; Lanza 2008), suppression of the stellar wind by preventing stellar magnetic loops from opening up (Cohen et al. 2010), triggering of stellar flares near the sub-planetary point (Lanza 2018; Fischer & Saur 2019), or sub-Alfvénic interaction, similar to the interaction seen in the Jupiter-Io system (Goldreich & Lynden-Bell 1969). In cases such as the Jupiter-Io interaction, where a planetary body is an obstacle in the flow of the plasma, Alfvénic waves are generated subsequent to the flow. The waves propagate along the magnetic field generating radiative energy, causing heating of the plasma (Gosling et al. 1982; Saur et al. 2013; Strugarek et al. 2014; Turnpenney et al. 2018).

Observational studies have reported some hints for tidal and magnetic interactions (Shkolnik et al. 2005; Pont 2009; Kashyap et al. 2008; Poppenhaeger & Wolk 2014; Maggio et al. 2015; Cauley et al. 2018), but also caveats have been pointed out with respect to biases from planet-detection methods which may skew activity distributions in planet host samples (Poppenhaeger et al. 2010; Miller et al. 2015). The intrinsic variability of stellar activity on short and long time scales, such as flares or stellar activity cycles, makes an unambiguous attribution of stellar activity changes to a planetary origin challenging.

GJ 1151 is a low-mass star located in the solar neighbourhood; we list its basic physical parameters in Table 1. The star was observed to display variable radio emission (Vedantham et al. 2020) with LOFAR (van Haarlem et al. 2013). Several scenarios for a purely stellar origin of the radio emission were excluded, and Vedantham et al. (2020) concluded that sub-Alfvénic star-planet interaction with a so far undetected small planet in a close orbit is the most likely explanation for the observed radio signatures.

Here we report on the first X-ray detection of GJ 1151, and we present an analysis of the star’s coronal properties in the context of star-planet interaction.

2 OBSERVATIONS AND DATA ANALYSIS

The star GJ 1151 was observed with XMM-Newton on 1st November 2018 for 12 ks (ObsID 0820911301, PI J. Schmitt). The observations used the medium filter and full frame mode for all three CCD detectors (MOS1, MOS2, and PN). We analysed the data using XMM’s SAS software version 18.0.0. We followed the standard data reduction steps outlined in
Figure 1. X-ray image of GJ1151 observed in the 0.2-2 keV energy band with XMM-Newton on 1st November 2018. The left panel shows the combined image from the two MOS cameras, the right panel shows the image extracted from the PN detector where the target position was located on a chip edge. GJ1151 is marked by a circle with a 20″ radius.

| Parameter    | Value               |
|--------------|---------------------|
| Gaia DR2 ID  | 786834302079285632a |
| 2MASS ID     | J11505787+4822395b   |
| G (mag)      | 11.694a             |
| J (mag)      | 8.488b              |
| H (mag)      | 7.952b              |
| K (mag)      | 7.637b              |
| mass         | 0.167 $M_\odot$c    |
| radius       | 0.190 $R_\odot$c    |
| distance     | 8.036 ± 0.008 pc$d$  |

Table 1. Fundamental physical parameters of the star GJ 1151. 

3 RESULTS

3.1 An X-ray detection of GJ 1151 with XMM-Newton

In Fig. 1 we show X-ray images from XMM-Newton’s MOS and PN cameras with the position of GJ1151 indicated. An excess is visible at the star’s position in all cameras, but weaker in PN due to the closeness of GJ 1151’s position to a detector chip edge.

To test whether GJ 1151 is significantly detected in X-rays, we used the Kraft-Burrows-Nousek (KBN) estimator (Kraft et al. 1991) as implemented in the python astropy package (Astropy Collaboration et al. 2013, 2018). The KBN estimator takes as input the number of detected photons in a source detection region and the expected number of background photons in the same region, estimated from a larger source-free area; it assumes both numbers follow Poisson statistics, as is appropriate for X-ray photon counting. The KBN estimator marginalises over the possible background photons in the source detect region, and yields a confidence interval for the source counts in the source detection region.

In the 0.2-2 keV energy band, we find 43 and again 43 counts in the source extraction region for MOS1 and MOS2, respectively. For the same time intervals and energy band we find 112 and 82 counts in the nine times larger background extraction region (i.e. an expected background count rate of 12.4 and 9.1 per exposure in the source extraction region for MOS1 and MOS2, respectively). For both detectors individually the KBN estimator yields a detection at > 3σ level.

When combining the signal from both MOS detectors for smaller uncertainties, we therefore have 86 photons in the source region and 194 counts in the larger background region, collected over a total exposure time of 10.46 + 10.46 = 20.91ks. We then derive a total number of background-subtracted source counts of $64.4^{+9.5}_{-8.9}$ with 1σ un-
certainties for both MOS detectors co-added, again using the Kraft-Burrows-Nousek estimator. This translates to a background-subtracted count rate of 3.1 counts per ks for the combined MOS detectors for GJ 1151 in the 0.2-2 keV energy band.

We also checked if there is significant flux at energies above 2.0 keV, and found that there is no significant excess of counts in the energy bands of 2-5 keV or 2-10 keV. This is consistent with GJ 1151 being a soft X-ray emitter, as expected for a low-activity star.

3.2 Temporal variability of GJ 1151’s corona

We extracted light curves with a time bin size of 1000 seconds from the source and background extraction regions of the two MOS cameras. We co-added the signal from the MOS cameras, and show the signal from the source region and the background regions (scaled to the source region size) in Fig. 2. The corona of GJ 1151 displays some variability: in the middle of the observation the stellar X-ray emission is indistinguishable from the background count rate, but at the beginning of the observation we seem to be witnessing the decay of a stellar flare. Unfortunately, the peak of the flare was not observed so that typical relations of flare decay times to the length of the flaring coronal loop (Reale 2007) can not be applied here. Another possibility for the shape of the light curve at the beginning of the observation is rotational modulation of the corona, with an active region rotating from the front of the star to the back. However, as GJ 1151 has a rotation period of more than 100 days, we consider this to be less likely than a flare decay.

There is also a short spike in the source signal towards the end of the observation, but since the background spikes at the same time and the source signal is compatible with the background within 2σ, it is unclear if this represents another flare or not.

We note for completeness that another mechanism for coronal brightness changes is the occurrence of coronal dimmings, which are observed to take place on our Sun after flares which are accompanied by coronal mass ejections (Hudson et al. 1996; Thompson et al. 1998). However, with the X-ray data present for GJ 1151 it is not possible to distinguish between coronal quasi-quiescence versus coronal dimmings caused by coronal mass ejections.

We tried to determine the number of excess counts after the flare has been excluded in order to quantify the quiescent flux of GJ 1151. We therefore compared the counts in the source and background regions for time stamps after the first 4000 seconds of the observation which resulted in a non-detection. The corresponding 3σ upper limit to GJ 1151’s count rate during this quiescent time stretch is 2.1 counts per ks for the combined MOS detectors in the 0.2-2 keV energy band.

3.3 GJ 1151’s coronal properties from X-ray spectra

We extracted CCD spectra of GJ 1151 from the data of the two MOS cameras. We used Xspec version 12 to fit the spectra with an APEC coronal plasma model (Smith et al. 2001; Foster et al. 2012), using solar-like coronal abundances from Grevesse & Sauval (1998). Since the number of excess counts is small, we decided to group the counts into bins of at least three photons and appropriately use the Cash statistic (Cash 1979) for spectral fitting. A single-temperature model did not yield a satisfactory fit, with a Cash statistic value of 35.9 with 28 degrees of freedom; the single-temperature model yielded a coronal temperature of 2.9 MK, but systematically underpredicted the spectral counts at energies below 0.5 keV. Therefore we used a two-component temperature model, which yielded a Cash statistic of value of 24.4 for 26 degrees of freedom. We note here that the Cash statistic, unlike the χ² statistic, does not yield a direct null hypothesis probability. However, the difference of the Cash statistic value between one model fit and another is dis-
ergy band of 0.1-2.4 keV, as was used by ROSAT, we find the spectrum is too low to allow such an analysis, which is why principle one would expect to see variation in the spectrum to the lower end of the detectors’ energy sensitivity and a component is not very well constrained, because it is close to the Sun, spectral effects of X-ray absorption by the interstellar medium. This places GJ 1151 among low-mass stars of low magnetic activity. We estimate GJ 1151’s bolometric luminosity to be $1.37 \times 10^{31}$ erg/s; we base this on GJ 1151’s mass of 0.167 $M_\odot$ as reported by Newton et al. (2017) and interpolate the bolometric luminosity from the tabulated values of Peacock & Mamajek (2013)\(^2\). Therefore GJ 1151’s coronal activity indicator is $\log L_X/L_{bol} = -4.4$ in the 0.2-2 keV energy band and -4.1 in the 0.1-2.4 legacy ROSAT energy band. This places GJ 1151 towards the lower end of the activity levels displayed by the very slowly rotating low-mass stars studied by Wright et al. (2018).

### 3.4 Consistency with previous upper limits

Two upper limits on GJ 1151’s X-ray luminosity exist, one from the ROSAT All-Sky Survey (RASS) and one from a Chandra ACIS-S observation (ObsID 18944, Chandra observation cycle 18, 2.9 ks exposure time, PI Wright).

Revisiting the Chandra observation, we find that there is actually a marginal excess of counts at the location of GJ 1151 in the 0.2-2 keV energy band, namely 3 X-ray photons in a circular region with 2″ radius placed at the nominal position of the star, versus a background signal of 0.041 expected counts for the same region size. This corresponds to a detection at 99.7% confidence level, albeit with a highly uncertain excess count measurement of 3.0±1.4 counts with 1σ uncertainties, or correspondingly 1.0±0.7 counts per ks \(^3\). Since Chandra’s ACIS-S detector has become less sensitive to very soft-energy photons due to a deposit accumulation on its filters, it actually traces mostly photons with energies above 0.7 keV in this observation.

If we use our best-fit model from XMM-Newton and use the ACIS-S effective area at the time of the Chandra observation, we would expect a count rate of 4.5 counts per ks. This is higher than what is seen in the Chandra observation, which means that the star is likely not flaring during the Chandra observation. If we choose to use the same underlying spectrum as seen in XMM-Newton, the detected Chandra count number corresponds to a flux of $1.8 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, which is likely an underestimate since GJ 1151’s coronal X-ray emission would be even softer when the star is not flaring. This is in overall agreement with Wright et al. (2018), who derive an upper limit from this Chandra observation for both the Chandra (0.5-8 keV) and ROSAT (0.1-2.4 keV) energy bands of $1.4 \times 10^{-14}$ and $2.0 \times 10^{-14}$, respectively. The small discrepancy to our detected flux seems to stem from their assumption of a coronal temperature around 0.5 keV, which is indeed often observed for fully convective M dwarfs, but is significantly lower in GJ 1151’s corona as the XMM-Newton detection shows.

The RASS observation only has an accumulated exposure time of about 370 s at the position of GJ 1151, cooler during the quiescent time, which would make the flux even lower than our upper limit.

### Table 2. Best-fit parameters of the two-temperature coronal model to the MOS data.

| Parameter       | Value          |
|-----------------|----------------|
| kF1 (keV)       | 0.095\(^{+0.05}_{-0.02}\) |
| norm1 ($x10^{-5}$) | $5.2^{+3.1}_{-2.6}$ |
| kF2 (keV)       | 0.74\(^{+0.17}_{-0.25}\) |
| norm2 ($x10^{-5}$) | 0.41\(^{+0.11}_{-0.09}\) |
| flux (erg cm$^{-2}$ s$^{-1}$), 0.2-2 keV | $7.1^{+0.7}_{-0.6} \times 10^{-14}$ |
| flux (erg cm$^{-2}$ s$^{-1}$), 0.1-2.4 keV | $1.4^{+0.7}_{-0.9} \times 10^{-13}$ |
| $L_X$ (erg s$^{-1}$), 0.2-2 keV | $5.2^{+0.5}_{-0.6} \times 10^{26}$ |
| $L_X$ (erg s$^{-1}$), 0.1-2.4 keV | $1.1^{+0.4}_{-0.7} \times 10^{27}$ |

\(^2\) updated table values available at https://www.pas.rochester.edu/~emamajek/EEM dwarf UBVIJHK colors Teff.txt

\(^3\) we note here that the low count numbers produce strong deviations from a Gaussian uncertainty regime. The $N\sigma$ confidence range is therefore no longer given by symmetrically multiplying the $1\sigma$ range limits by a factor of $N$. 

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This paper has been accepted in the Monthly Notices of the Royal Astronomical Society (MNRAS). The final published version will be available at https://academic.oup.com/mnras.

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\(^2\) The values used in this analysis are from the updated table available at https://www.pas.rochester.edu/~emamajek/EEM dwarf UBVIJHK colors Teff.txt

\(^3\) We note that the low count numbers produce strong deviations from a Gaussian uncertainty regime. The $N\sigma$ confidence range is therefore no longer given by symmetrically multiplying the $1\sigma$ range limits by a factor of $N$.
corresponding to a non-restrictive upper limit of $1.5 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2}$ in the native ROSAT energy band of 0.1-2.4 keV, using our measured average coronal temperature of 1.6 MK.

4 DISCUSSION

The coronal X-ray brightness of GJ 1151 is not unusual for low-activity M dwarfs. Similar X-ray activity levels have been found for slowly rotating M dwarfs by Wright et al. (2018). However, in the case of GJ 1151 we were able to show that its corona is of a very low temperature, which means that a considerable fraction of its X-ray flux is to be found at very soft energies below 0.3 keV.

Other slowly-rotating M dwarfs have been found to flare occasionally, see for example Raetz et al. (2020), so the fact that GJ 1151 as a low-activity star happens to flare in the XMM-Newton observation is not extraordinary.

In the context of star-planet interactions, the coronal properties we derived for GJ 1151 from our X-ray detection do not contradict the model presented by Vedantham et al. (2020), who based their analysis on the X-ray upper limits available at that time. Specifically, Vedantham et al. (2020) excluded radio flares as an explanation of the radio observations based on an assumed coronal temperature of 2 MK. This is very close to our measured average coronal temperature of 1.6 MK, and following the outlined calculations in Vedantham et al. (2020) a lower coronal temperature would lead to an even lower radio brightness temperature, strengthening their exclusion of radio flares as an explanation. Unfortunately, since the peak of the flare was not included in the X-ray observation, it is not possible to draw further inferences on the flare properties, such as loop length or any type of density analysis of the flaring loop.

The star-planet interaction scenario with open stellar field lines used by Vedantham et al. (2020) assumes a coronal temperature of 1 MK as the base for the stellar wind, and this can be considered realistic given our analysis. Since the X-ray observation contains a flare and the measured coronal temperature, averaged over the full observation, is 1.6 MK, one can assume that the corona of GJ 1151 is even cooler during quiescent times. The relationship of lower X-ray luminosities with lower coronal temperatures is very well established (Telleschi et al. 2005; Schmitt 1997; Güdel et al. 1997; Johnstone & Güdel 2015). We note that the Poynting flux derived by Vedantham et al. (2020) of $F_P \sim 10^{23} \text{erg s}^{-1}$ is so low that a direct detection of coronal emission induced by star-planet interaction of GJ 1151 with a nearby planet is not in the feasible range for current X-ray observatories.

5 CONCLUSIONS

We have detected coronal X-ray emission from the M dwarf star GJ 1151, using XMM-Newton. The star displays coronal variability, a low coronal temperature of 1.6 MK and an average X-ray luminosity of $5.5 \times 10^{26} \text{erg s}^{-1}$ in the 0.2-2 keV energy band. The detected X-ray emission is compatible with a reported scenario of sub-Alfvénic star-planet interaction, motivated by the star’s observed emission at radio wavelengths.

ACKNOWLEDGEMENTS

The authors thank J. Callingham and H. Vedantham for helpful discussions. This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. Part of this work was supported by the German Leibniz-Gemeinschaft under project number P67-2018.

DATA AVAILABILITY

The data used here is publicly available in ESA’s XMM-Newton data archive.

REFERENCES

Astropy Collaboration et al., 2013, A&A, 558, A33
Astropy Collaboration et al., 2018, AJ, 156, 123
Bailer-Jones C. A. L., Rybizki J., Fouesneau M., Mantelet G., Andrae R., 2018, AJ, 156, 58
Cash W., 1979, ApJ, 228, 939
Cauley P. W., Shkolnik E. L., Llama J., Bourrier V., Moutou C., 2018, AJ, 156, 262
Cohen O., Drake J. J., Kashyap V. L., Sokolov I. V., Gombosi T. I., 2010, ApJ, 723, L64
Cuntz M., Saar S. H., Musielak Z. E., 2000, ApJ, 533, L151
Fischer C., Saur J., 2019, ApJ, 872, 113
Foster A. R., Ji L., Smith R. K., Brickhouse N. S., 2012, ApJ, 756, 128
Gaia Collaboration et al., 2018, A&A, 616, A1
Goldreich P., Lynden-Bell D., 1969, ApJ, 156, 59
Gosling J. T., Asbridge J. R., Bame S. J., Feldman W. C., Zwickl R. D., Paschmann G., Schloemen N., Russell C. T., 1982, J. Geophys. Res., 87, 239
Grevesse N., Sauval A. J., 1998, Space Sci. Rev., 85, 161
Güdel M., Guinan E. F., Skinner S. L., 1997, ApJ, 483, 947
Hudson H. S., Acton L. W., Freeland S. L., 1996, ApJ, 470, 629
Irwin J., Berta Z. K., Burke C. J., Charbonneau D., Nutzman P., West A. A., Falco E. E., 2011, ApJ, 727, 56
Johnstone C. P., Güdel M., 2015, A&A, 578, A129
Kashyap V. L., Drake J. J., Saar S. H., 2008, ApJ, 687, 1339
Kraft R. P., Burrows D. N., Nousek J. A., 1991, ApJ, 374, 344
Lanza A. F., 2008, A&A, 487, 1163
Lanza A. F., 2018, A&A, 610, A81
Maggio A., et al., 2015, ApJ, 811, L2
Miller B. P., Gallo E., Wright J. T., Pearson E. G., 2015, ApJ, 799, 163
Newton E. R., Irwin J., Charbonneau D., Berlind P., Calkins M. L., Mink J., 2017, ApJ, 834, 85
Pecaut M. J., Mamajek E. E., 2013, ApJS, 208, 9
Pillitteri I., Wolk S. J., Scortino S., Antoci V., 2014, A&A, 567, A128
Pont F., 2009, MNRAS, 396, 1789
Poppenhaeger K., Wolk S. J., 2014, A&A, 565, L1
Poppenhaeger K., Rohrade J., Schmitt J. H. M. M., 2010, A&A, 515, A98
Raetz S., Stelzer B., Damasso M., Scholz A., 2020, arXiv e-prints, p. arXiv:2003.11937
Reale F., 2007, A&A, 471, 271
Saur J., Grambusch T., Duling S., Neubauer F. M., Simon S., 2013, A&A, 552, A119
Schmitt J. H. M. M., 1997, A&A, 318, 215
Shkolnik E., Walker G. A. H., Bohleender D. A., Gu P. G., Kürster M., 2005, ApJ, 622, 1075
Skrutskie M. F., et al., 2006, AJ, 131, 1163
Smith R. K., Brickhouse N. S., Liedahl D. A., Raymond J. C., 2001, ApJ, 556, L91
Strugarek A., Brun A. S., Matt S. P., Réville V., 2014, ApJ, 795, 86
Telleschi A., Güdel M., Briggs K., Audard M., Ness J.-U., Skinner S. L., 2005, ApJ, 622, 653
Thompson B. J., Plunkett S. P., Gurman J. B., Newmark J. S., St. Cyr O. C., Michels D. J., 1998, Geophys. Res. Lett., 25, 2465
Turnpenney S., Nichols J. D., Wynn G. A., Burleigh M. R., 2018, ApJ, 854, 72
Vedantham H. K., et al., 2020, Nature Astronomy,
Wright N. J., Newton E. R., Williams P. K. G., Drake J. J., Yadav R. K., 2018, MNRAS, 479, 2351
van Haarlem M. P., et al., 2013, A&A, 556, A2

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