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Implications of stellar activity for exoplanetary atmospheres

P. Odert[1], M. Leitzinger[1], A. Hanslmeier[1], H. Lammer[2], M.L. Khodachenko[2] and I. Ribas[3]

[1]*Institute of Physics/IGAM, University of Graz, Universitätsplatz 5, 8010 Graz, Austria*
e-mail: petra.odert@uni-graz.at
[2]*Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, 8042 Graz, Austria*
[3]*Institut de Ciències de l'Espai (CSIC-IEEC), Facultat de Ciències, Torre C5, parell, 2a pl, Campus UAB, 08193 Bellaterra, Spain*

Abstract: Stellar X-ray and extreme ultraviolet (XUV) radiation is an important driver of the escape of planetary atmospheres. Young stars emit high XUV fluxes that decrease as they age. Since the XUV emission of a young star can be orders of magnitude higher compared to an older one, this evolution has to be taken into account when studying the mass-loss history of a planet. The temporal decrease of activity is closely related to the operating magnetic dynamo, which depends on rotation and convection in Sun-like stars. Using a sample of nearby M dwarfs, we study the relations between age, rotation and activity and discuss the influence on planets orbiting these low-mass stars.

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Introduction

The discovery of the first exoplanet orbiting a solar-like star (Mayor & Queloz 1995) surprised researchers with the fact that a gaseous planet was found at a close distance to its host star, contrary to what is known from our Solar System. Since then, a large number of such 'Hot EGPs' (Extrasolar Giant Planets) has been discovered. That raised many questions concerning the formation, evolution and long-term stability of such objects. Many studies have shown that atmospheric mass loss via thermal and non-thermal processes plays an important role (Yelle *et al*. 2008 and references therein). These processes are mainly driven by the radiation and particle emissions of the host star. Therefore, a good knowledge of stellar properties, including their evolution, is crucial for the understanding of the effects on planets.

M-type stars are the most numerous stars in the galaxy (Tarter *et al*. 2007). This fact, together with their long lifetimes and slow evolution, make them promising targets for exoplanet searches. However, M-type stars are also known to exhibit high levels of short-wavelength X-ray and extreme ultraviolet (XUV; $\lambda \sim 0.1$–100 nm) radiation, as well as frequent and powerful flare events during extended periods of time (Scalo *et al*. 2007). This has important implications for planetary atmospheres, as thermal mass loss is mainly driven by the incoming stellar XUV radiation. In addition, such extreme short-wavelength fluxes could be harmful to possible life on planets orbiting inside their habitable zones, which are located closer to the star, as they are for solar-type stars.

It is well established that stellar rotation, age and magnetic activity are closely related in solar-like and cooler dwarf stars (Güdel 2007 and references therein). Stellar rotation and convection are the basis of the magnetic dynamo, which produces a variety of stellar activity phenomena, including strong XUV radiation, spots, flares and coronal mass ejections (CMEs). The depth of the convection zone is mainly a function of stellar mass. As convection is more efficient for lower-mass stars, the magnetic dynamo is also more efficient for lower masses for equal rotation periods. With the increasing age of a star, it spins down due to angular momentum loss via stellar winds. The rotation period decreases with time, leading to a decrease of the dynamo strength and, hence, weakening of related activity phenomena. This temporal activity decrease is faster for higher-mass stars. For high rotation rates, a saturation of activity can be observed. Understanding the evolution of stellar activity and its dependence on other stellar properties, such as age, spectral type or rotation, is crucial for the understanding of the evolution of planets and their atmospheres.

Activity of M-type stars

In order to study the characteristics of M dwarfs in view of their prospects as habitable planet hosts, we have compiled a sample of nearby M dwarfs within 15 pc of the Sun and collected relevant data from literature (Odert *et al*. 2008). As a proxy for the overall stellar activity, we use the X-ray luminosity calculated from Röntgen Satellite (ROSAT) data, which operated in the 0.6–12.4 nm range. The ROSAT performed

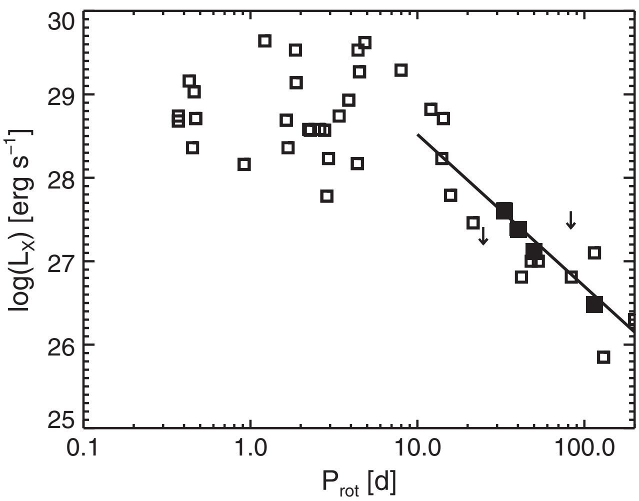

Fig. 1. Stellar X-ray luminosity as a function of the rotation period. Empty squares are single stars from our sample, filled symbols indicate stars with known exoplanets and downpointing arrows indicate upper limits of the X-ray luminosity. The solid line is the fit to the non-saturated stars.

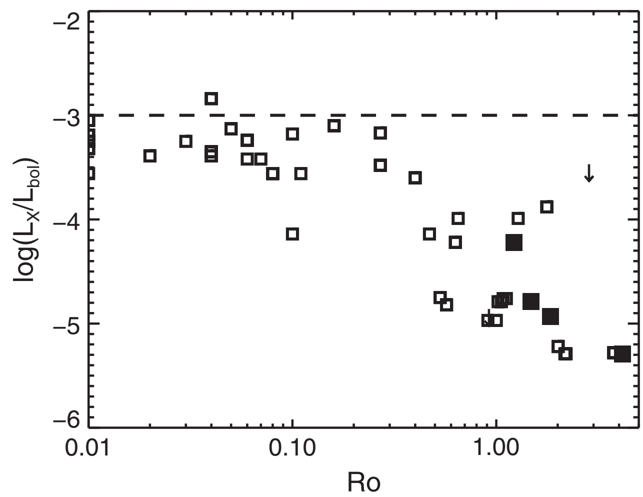

Fig. 2. Ratio between X-ray luminosity and bolometric luminosity as a function of magnetic Rossby number. Symbols as in Fig. 1. The dashed line indicates the saturation level of −3.

an all-sky survey (RASS), as well as pointed observations (PSPC). Typical exposure times were tens to hundreds of seconds for the RASS and up to several ks for PSPC. For our study, count rates from observations with the longest exposure times available, either from the RASS or PSPC, have been used. X-ray count rates were compiled from the NEXXUS database (Schmitt & Liefke 2004; http://www.hs.uni-hamburg.de/DE/For/Gal/Xgroup/nexxus/nexxus.html) and converted to flux units as described in Schmitt & Liefke (2004). Several of the planet-hosting M-type stars are very inactive and were therefore not detected by the ROSAT. For these stars, upper limits on their X-ray luminosity were determined using their distance and the ROSAT's characteristic limiting flux of $2\times10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (Schmitt *et al.* 1995).

Whereas X-ray data is available for the largest part of the sample, rotation periods are only known for a small number of stars, namely 49. Therefore, the sample was supplemented with 18 additional M dwarfs outside of 15 pc. All rotation periods used are photometric periods from starspot modulation.

Figure 1 shows the resulting correlation of the rotation period and the X-ray luminosity. Only data for single stars were used, because many binaries are not resolved in the ROSAT data. Two regimes are clearly visible. For rotation periods below 10 d, the X-ray luminosity has a plateau with a large spread of about two orders of magnitude ($\sim$27.7–29.7 $\mathrm{erg\,cm^{-2}\,s^{-1}}$). This is the saturated regime in which the coronal activity seems to be independent of rotation. For periods longer than 10 d, the X-ray luminosity decreases with a slope of ~ -1.8 and the spread is much smaller. Known M dwarfs with planets are indicated. They are located in the non-saturated regime exclusively.

The magnetic Rossby number $Ro = P_{\mathrm{rot}}/\tau_c$ describes the efficiency of the magnetic dynamo. Kiraga & Stepien (2007) provide average τ_c values for several mass ranges in the M-star domain. We assign these average values to our sample stars depending on their masses to calculate Ro.

The relation between Rossby number and activity index $\log(L_X/L_{\mathrm{bol}})$ is shown in Fig. 2. The advantage of using this relation is that it is independent of mass. Again, the exoplanet hosts lie well below the known saturation limit of $\log(L_X/L_{\mathrm{bol}})\approx -3$, which is indicated by a dashed line.

In Odert *et al.* (2010a,b) we determined ages for the M dwarfs in our sample using three different methods: (1) established membership in stellar moving groups or associations of known age; (2) Ca II activity-age calibrations; (3) gyrochronology (rotation period-age calibrations). Although all used methods have their advantages and weaknesses, it was shown that the results generally agree rather well with the average M-star X-ray evolution derived from clusters (Penz & Micela 2008).

This mean evolution is shown in Fig. 3, together with the derived values for known planet hosts. Discrepant age estimates for the same star are connected by dashed lines.

Thermal mass loss of close-in exoplanets

Stellar XUV radiation heats the upper planetary atmosphere and leads to escape. For close-in planets, tidal forces become important, because the Roche lobe distance is located deeper in the planetary atmosphere, and atmospheric material above this distance can escape freely into space. To simulate the thermal mass loss of exoplanets we follow the approach of Lammer *et al.* (2009). They used the energy-limited formula of Erkaev *et al.* (2007) and calculated mass-loss rates over evolutionary timescales of all known transiting exoplanets known at this time. The stellar XUV evolution was approximated by the X-ray evolution derived from cluster data

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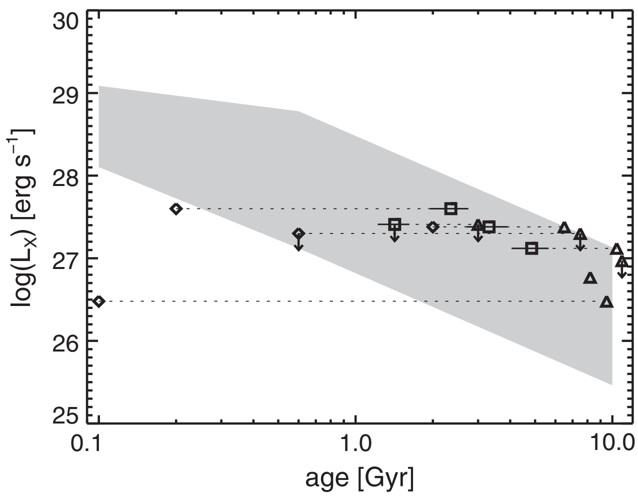

Fig. 3. Evolution of X-ray luminosity with age for known exoplanet hosts. Diamonds indicate ages by moving group membership, triangles ages derived from Ca II activity, and squares are gyrochronology ages (formal errors are shown as solid lines). Downward arrows indicate X-ray upper limits. The shaded area illustrates the average X-ray evolution of M-type stars derived from cluster distributions (Penz & Micela 2008). Different age estimates for the same star are connected by dashed lines.

(Penz *et al.* 2008, Penz & Micela 2008), because the largest part of the EUV range is unobservable due to interstellar absorption. The radius evolution of the planet was described by the empirical law given in Lecavelier des Etangs (2007). Lammer *et al.* (2009) discussed appropriate values for the heating efficiency, which is defined as the ratio of the net heating rate to the rate of stellar energy absorption, and concluded that values of 10–25% were the most realistic. The onset of atmospheric escape during the planetary evolution depends on the exosphere formation time and was derived by Lammer *et al.* (2007) to lie between 50 and 300 Myr.

Figure 4 shows the dependence of atmospheric mass loss on the orbital radius and the mean planetary density for four scenarios of stellar and planetary mass. Combinations of two sample planets with masses of 1 M_{Jup} and 1 $M_{Nep} \approx 0.05$ M_{Jup} orbiting two sample stars with masses of 0.5 M_{Sun} (corresponding to an early M dwarf) and 1 M_{Sun} (corresponding to a Sun-like G star) were studied. Planets with mean densities between 0.25 and 1.5 g cm^{-3} have been placed in orbits of 0.01–0.025 AU around the star. A heating efficiency of 25% has been used. The planets were allowed to evolve between 50 Myr and 5 Gyr. The resulting atmospheric mass loss is shown in percentage of the initial planetary mass. It can be clearly seen that massive planets orbiting low-mass stars experience negligible losses, except for combinations of very low density and extremely close orbits. Planets with lower masses are more strongly affected, particularly if they orbit solar-like stars.

Discussion

We studied the relations between activity, rotation and age of a sample of nearby M dwarfs. Generally, our results are in good agreement with previous studies. The correlation between X-ray luminosity and rotation period confirms the findings by Pizzolato *et al.* (2003), namely a saturated regime for periods shorter than 10 d and decreasing $\log L_X$ with increasing period for slower rotators. Our fit to the non-saturated regime yields a slope of ~ -1.8, which is similar to the value of -2 found by Pizzolato *et al.* (2003). The correlation between the activity parameter $\log(L_X/L_{bol})$ and the magnetic Rossby number also show a saturated regime close to the expected value of -3 for Rossby numbers smaller than about 0.2 and a decay for larger *Ro*. These findings are similar to the results of Reiners *et al.* (2009), who found the transition between saturated and non-saturated regime at $Ro = 0.1$. However, the transition between regimes in this plot is not as clear as for L_X versus P_{rot}, so it is difficult to recognize the transition value of *Ro* due to the sparsity of data in the interval $Ro = 0.1$–0.4. Known exoplanet host stars are located in the non-saturated regimes exclusively.

Ages of these planet-hosting stars have been estimated by three different methods (Odert *et al.* 2010a,b) and compared with the X-ray luminosity evolution from cluster data (Penz & Micela 2008). Different age determination methods yield in many cases very different results for the same star. Soderblom (2010) thoroughly discussed the problems of stellar age determination. All methods applied herein are – directly or indirectly – calibrated on cluster stars. Therefore, the precision of ages and their calibrations against other quantities is limited by many factors, such as the determination of cluster ages themselves, possible age spread in clusters, intrinsic spread of activity/rotation of coeval stars, lack of observations of the faint M-type star members of clusters, and hence uncertain calibrations in this mass regime, uncertainty in cluster membership (non-members can share cluster kinematics by chance), and the lack of nearby clusters with ages >600 Myr for calibration of older ages. The average X-ray evolution of Penz & Micela (2008) can be used to constrain age estimates derived by other methods. However, most of the discrepant ages lie between the boundaries of their given age regime for given X-ray luminosity, which spans a large age range.

When comparing thermal mass-loss rates of exoplanetary atmospheres for planets orbiting G and M dwarfs, it can be seen that they are higher for the higher-mass G stars. The mass-loss enhancement factor due to tidal forces (cf. Erkaev *et al.* 2007, Lammer *et al.* 2009) is larger for higher stellar masses for given values of planetary density and orbital distance, and therefore more important for G-type stars than for M dwarfs. In addition, XUV fluxes at a given orbit are higher for G-type stars (assuming roughly the same ages) due to the much lower luminosity of M-type stars (e.g. Penz & Micela 2008), making thermal losses more efficient. The mass loss is higher for lower-mass planets, because the percentage is higher for a given absolute lost mass (in g) during a certain time interval. A scaling in absolute values would yield no difference between the 'Jupiter' and 'Neptune' plots, because the mass-loss rate only depends on

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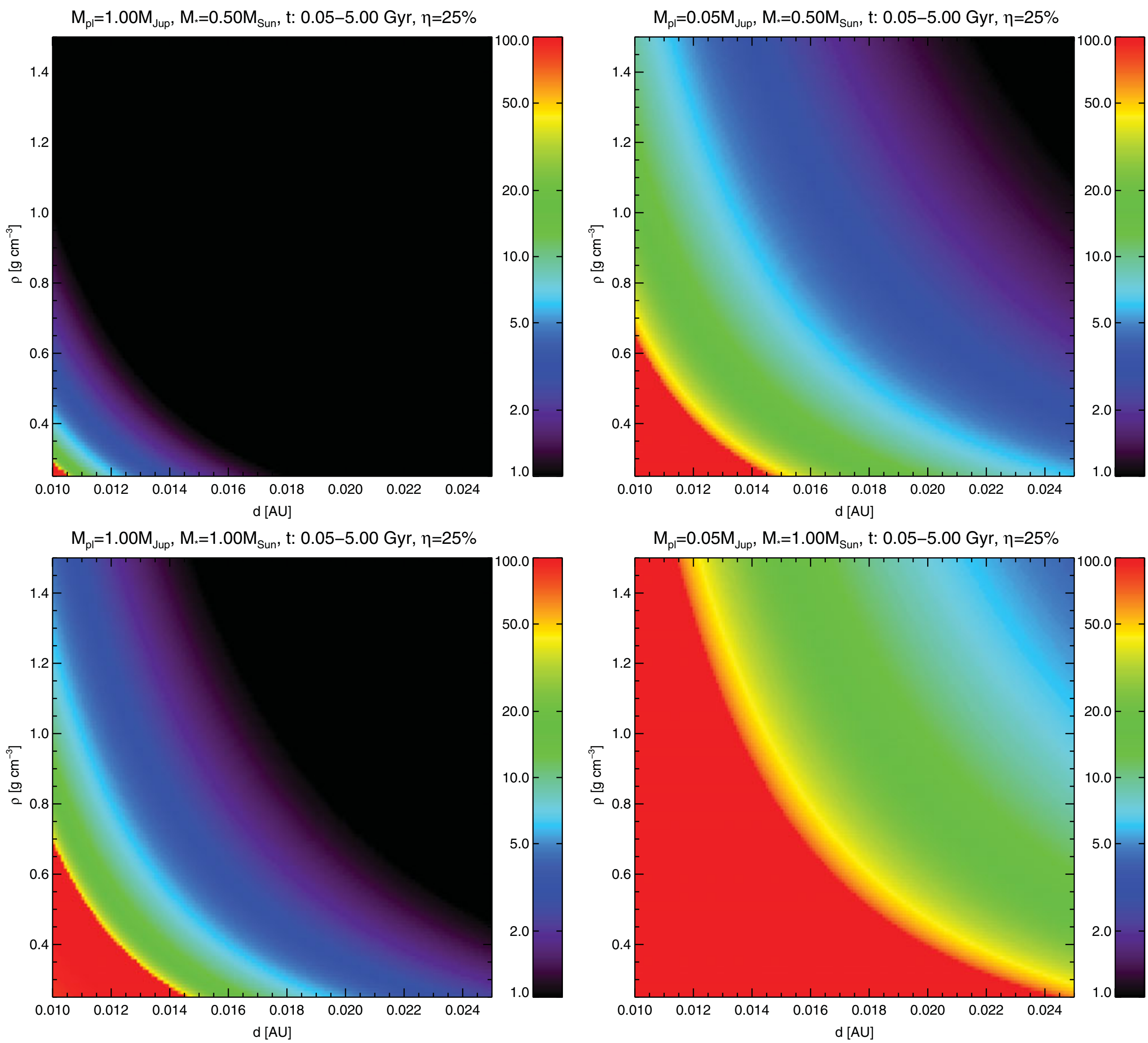

Fig. 4. Theoretical thermal mass-loss rates of two exoplanets with masses of 1 M_{Jup} and 1 $M_{Nep} \approx 0.05$ M_{Jup} orbiting an M-type star ($M_* = 0.5$ M_{Sun}) and a G star ($M_* = 1$ M_{Sun}) as a function of mean planetary density ρ and orbital radius d. The mass loss was integrated between 0.05 and 5 Gyr using a heating efficiency of 25%. Losses are given in percentage of the initial planetary mass.

mean planetary density, orbital distance, stellar mass and XUV flux (cf. equations in Lammer *et al.* 2009). Orbital migration was neglected in these plots, but it is obvious that the mass loss would increase if the planets moved even further inwards from the assigned locations with time. On the other hand, if the planets would form farther outside and move to these close orbits at later stages, the total mass loss would be reduced.

Conclusions

Correlations between X-ray activity and rotation for a sample of nearby M dwarfs confirm previous results, showing clearly a saturated regime and a non-saturated region with a typical decay behaviour. Ages of the exoplanet host stars were determined, but the often-discrepant results clearly show the problem of stellar age determination, particularly in the low-mass regime. Thermal mass-loss rates of two sample exoplanets orbiting low-mass M-type stars and solar-like G-type stars are studied for a range of densities and orbital distances, showing that this process is most severe for massive stars and low-mass planets.

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