POSSIBLE CONSTRAINTS ON EXOPLANET MAGNETIC FIELD STRENGTHS FROM PLANET–STAR INTERACTION

Caleb A. Scharf
Columbia Astrobiology Center, Columbia Astrophysics Laboratory, 550 West 120th Street, New York, NY 10027, USA; caleb@astro.columbia.edu
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ABSTRACT

A small percentage of normal stars harbor giant planets that orbit within a few tenths of an astronomical unit. At such distances, the potential exists for significant tidal and magnetic field interaction resulting in energy dissipation that may manifest as changes within the stellar corona. We examine the X-ray emission of stars hosting planets and find a positive correlation between X-ray luminosity and the projected mass of the most closely orbiting exoplanets. We investigate possible systematics and observational biases that could mimic or confuse this correlation but find no strong evidence for any, especially for planets more massive than \( \sim 0.1 M_J \). Luminosities and upper limits are consistent with the interpretation that there is a lower floor to stellar X-ray emission dependent on close-in planetary mass. Under the hypothesis that this is a consequence of planet–star magnetic field interaction, and energy dissipation, we estimate a possible field strength increase of a factor of \( \sim 8 \) between planets of 1 and 10 \( M_J \).

Intriguingly, this is consistent with recent geodynamo scaling law predictions. The high-energy photon emission of planet–star systems may therefore provide unique access to the detailed magnetic, and hence geodynamic, properties of exoplanets.

Key words: planetary systems – stars: activity

Online-only material: color figures

1. INTRODUCTION

Surveys for exoplanets have revealed a population of objects that orbit with very short periods (e.g. Marcy et al. 2005). The potential therefore exists for significant tidal and magnetic interaction between these planets and their host stars (Cuntz et al. 2000; Ip et al. 2004; Preusse et al. 2006; McIvor et al. 2006; Cranmer & Saar 2007).

Tidal evolution of planetary orbits, while still subject to significant uncertainty (due to the poorly constrained tidal quality factor \( Q_p \), e.g., Matsumura et al. 2008), is well established (e.g., Jackson et al. 2008 and references therein). Tidal dissipation within planetary atmospheres is also a potentially important energy source in models of gas giant characteristics (e.g., Ibugi & Burrows 2009). In many cases, the tidal evolution is dominated by the torques on the bulge raised on a planet by its parent star. However, for the most massive and closest orbiting planets, significant torques are also possible due to the bulges raised in the stellar atmosphere. These modify the orbital evolution of the planet and act (for prograde planetary orbits) to maintain a higher observed spin rate for the host stars at a given age. Such an effect has been claimed in studies of exoplanet host star rotational velocities (Pont 2009), enhanced UV luminosities (Shkolnik et al. 2008), and at least one system—\( \tau \)-Booïs—shows evidence for stellar synchronicity with a planetary orbit (Walker et al. 2008). It is also well established that main-sequence stellar X-ray luminosity is correlated with stellar rotation rates (Ayres & Linsky 1980; Pallavicini et al. 1981; Maggio et al. 1987; see below), which are generally higher for the youngest objects.

Magnetic field interaction between stars and planets is likely complex, but is expected to exhibit distinctly different characteristics to tidally induced phenomena. In particular (and see below), we might expect stellar variations directly related to planetary orbital phase and correlation with planetary mass and orbital parameters. There is growing evidence from the study of stellar photometry (Walker et al. 2008), chromospheric emission (Shkolnik et al. 2008), and X-ray emission (Kashyap et al. 2008; Poppenhaeger et al. 2010) that interaction of this nature is indeed occurring between stars and planets—at least in certain cases. Furthermore, although the physical origin is not clear, Hartman (2010) finds a robust correlation between stellar chromospheric activity and the surface gravity of transiting hot Jupiters.

X-ray emission from the stellar corona is a particularly interesting probe of star–planet interaction. Coronal X-ray photons originate from thermal bremsstrahlung, and inner atomic transitions of the hot, \( 10^6 \)–\( 10^7 \) K, plasma. The general heating mechanisms in stellar coronae are still largely unknown, but appear to be intimately related to magnetic field structures and complex transfer of energy from the stellar surface (Aschwanden 2004; Jess et al. 2009). The placement of a planet, particularly a gas giant of Jupiter mass or greater, in proximity to the stellar coronal magnetic field may affect the transport and release of energy in the plasma and therefore the high-energy photon output. Indeed, if stellar coronal magnetic field alignment favors strong coupling with planetary magnetospheres then significant, time-dependent, energy release may occur. Estimates suggest excess X-ray emission in the range of \( \sim 10^{27} \) erg s\(^{-1} \) to as much as an order of magnitude variation in the quiescent stellar X-ray luminosity is possible (Ip et al. 2004; Lanza 2008, 2009; Cohen et al. 2009).

Stellar X-ray emission is of course determined by a variety of systematic and stochastic components, related to fundamental stellar activity (see above). The addition of an emission component that may vary on timescales commensurate with a planetary orbit poses a challenge for observations. At the distances for which both magnetic and tidal interactions are expected to become significant (\( \sim 0.1 \)–\( 0.2 \) AU), orbital periods will range from \( \sim 1 \) to \( \sim 20 \) days (assuming stellar masses close to 1 \( M_\odot \)). Many X-ray pointed observations of nearby stars span only a few hours and may not adequately sample the possible planet-induced emission variation. Current techniques of planet detection (O’Toole et al. 2009) are also significantly dependent on...
overall stellar activity, introducing further observational biases in sample selection.

In order to further investigate the possibility of coronal emission signatures correlated with close planetary companions, we use a sample of exoplanet host stars within 60 pc with both X-ray detections and upper limits from the ROSAT mission all-sky survey. We describe these data in Section 2 and discuss its unique, partially time-averaged, characteristics which are well suited to this problem. We examine the detailed relationship of X-ray luminosities and upper limits to planetary properties (Sections 2.1 and 3), and examine potential sources of bias (Section 4). In Section 5 we consider tidal effects, and in Section 6 we consider planet–star magnetic field interaction and the possible interpretation of our results. In Section 7, we discuss and summarize our results and conclude in Section 8.

2. EXOPLANET SAMPLE AND X-RAY DATA

The ROSAT mission produced an all-sky survey of X-ray sources in the 0.1–2.4 keV energy band, released as a Bright Source Catalog (BSC; Voges et al. 1999) and a deeper, but less uniform Faint Source Catalog (FSC). In total ∼114,000 sources were detected.

Existing observations of planet-hosting stars suggest that X-ray emission triggered by a planet may be modulated over time, phase-shifted from the planetary orbital phase, and not necessarily in a precisely repeating pattern (Shkolnik et al. 2005, 2008; Walker et al. 2008). Typical exposure times on our targets in the BSC and FSC ROSAT catalogs range from ∼400 s to ∼1000 s, however, these represent accumulated exposure times from the ∼6 month all-sky scan performed by ROSAT—wi ...
fraction of the systems with upper limits are the result of transit survey detections (which is strongly biased to short-period objects due to the geometrical detection probability) at distances of over 100 pc, with subsequent radial velocity (RV) follow up. While imposing a volume limit is not ideal, it does effectively remove this highly biased population. The final conclusions reached here are not significantly altered by the effect of this distance cut. Our resulting set of X-ray upper limits is then reduced to 42 systems with periastron within 0.15 AU and 99 systems with periastron greater than 0.15 AU.

2.1. Inner and Outer Planet Subsamples

To divide the planet-hosting stellar sample between those with a high potential for magnetic field or tidal interaction and those without, we evaluate the periastron distance ($d_{\text{peri}}$) of the innermost planet (Table 1). An inner subsample is defined for systems where $d_{\text{peri}} < 0.15$ AU. This choice of distance is commensurate with that used in earlier studies (Kashyap et al. 2008) and represents an orbital period of $\sim 20$ days around a one solar-mass star, within which tidal interactions between star and planet become dynamically important (Goldreich & Soter 1966) and orbital velocities are similar to coronal field rotation velocities (Lanza 2009, and below). Our conclusions are unaltered for variations in this distance of $\pm 0.05$ AU.

Our statistical examinations of these data are made using the survival analysis methods of the ASURV version 1.2 software package (Isobe & Feigelson 1990; Lavalley et al. 1992) that allows for “censoring” (i.e., upper limits) and univariate and bivariate tests by implementing the methods presented in Feigelson & Nelson (1985) and Isobe et al. (1986). Thus, both detections and upper limits are incorporated into all statistical tests in a self-consistent and robust fashion.

In Table 2, we present the results of a Kaplan–Meier (K-M) estimation of the underlying distribution of the inner and outer sample X-ray luminosities. The two samples agree well in all but the 75th percentile of the low $L_x$ end of the distributions, where there is a difference of $\Delta \log_{10} L_x \sim 6.5$. This is directly attributable to the lowest $L_x$ detections occurring in the inner sample only. As we discuss further below, this may be due to the observational biases of the RV planet-detection method, wherein the very least massive planets are only detectable on close orbits around low-activity stars. In all other respects, the inner and outer samples show statistically similar $L_x$ distributions. The means differ by approximately one standard deviation. We caution though that K-M means and medians are not reliable for very heavily censored data, and that our present samples include significant numbers of censored points (upper limits). Nonetheless, these results are in general agreement with the work of Poppenhaeger et al. (2010) who find no excess emission
from planet-hosting stars in general. Our results do not support the findings of Kashyap et al. (2008), who claim as much as a factor of four emission enhancement.

We also apply tests to determine whether the two censored populations are drawn from the same underlying distribution. A Gehan generalized Wilcoxon test (that assumes the same censoring pattern applies to both samples being compared) yields probabilities of 91.99% (permutation variance) and 92.11% (hypergeometric variance, more robust to censoring pattern differences) that the $L_x$ detections and upper limits of the inner and outer planetary samples are indeed drawn from the same physical distribution.

In summary, there does not appear to be any significant difference in the $L_x$ distributions of the inner and outer sub samples, especially if we allow for observational biases that particularly affect the lowest mass planet detections.

### 3. PLANET MASS VERSUS $L_x$ CORRELATIONS

We examine the detailed relationship between measured planetary properties and system X-ray emission in our sample. In Figure 1, detected X-ray luminosity is plotted versus the RV-derived planetary mass ($M_p \sin i$, projected by the typically unknown system inclination) for the outer ($d_{peri} > 0.15$ AU) and inner ($d_{peri} < 0.15$ AU) planetary sub samples. The presence of the lowest mass planets in only the inner sample is a result of biases in planet-detection techniques. For a given instrumental RV sensitivity then the lowest mass planets are only detectable on short orbits. Furthermore, the least active stars are favored for the detection of small RV variations and lower mass planets. In Section 4.1, we examine the residual stellar “jitter” in our sample systems and this bias in more detail. However, there is also a clear difference between the distributions seen for planets with $M_p \sin i > 0.1 (M_J)$ between the inner and outer sub samples that is not readily explained by observational biases. $L_x$ shows a correlation with $M_p \sin i$ for the inner sub sample that is not evident in the outer sub sample.

In Figure 2, we plot detected X-ray luminosities and upper limits versus projected planet mass for the inner and outer sub samples. For the inner planet sub sample the distribution of upper limits appears to be consistent with a population of sources that either follows the power-law fit seen in detected systems or has a lower bound or “floor” that correlates with planet mass ($M_p \sin i$). A notable outlier in the upper limits of this sub sample is labeled as “a” in the inner planet panel of Figure 2. This point corresponds to the GL 86 system at an 11 pc distance, with a single ~4 $M_J$ planet at 0.11 AU semimajor axis and eccentricity $e = 0.046$. GL 86 A is a K0V star in a likely binary configuration with a 0.5 $M_\odot$ white dwarf companion (GL 86 B) at ~20 AU separation (Lagrange et al. 2006). Furthermore, there is a potential X-ray detection at 0.63 arcmin separation, just beyond our search radius. If that source is at the distance of GL 86 it has $L_x \sim 6(\pm 1) \times 10^{27}$ erg s$^{-1}$, commensurate with our estimated upper limit at that location. The history of this system is somewhat uncertain, and the presumed earlier presence of a ~2 $M_\odot$ GL 86 B stellar progenitor (Lagrange et al. 2006) at smaller separation raises considerable uncertainty about the environmental history of the planet GL 86 b and its parent star.

Applying the tools of survival analysis we find that for all objects in the outer sample a generalized Kendall statistic yields a 26.4% probability that no correlation is present between $L_x$ and $M_p \sin i$. A generalized Spearman’s $\rho$ test yields an 11.3% probability of no correlation. By contrast, for all objects in the inner planet sample the generalized Kendall strongly indicates the presence of a correlation, with only 0.01% probability that there is none, and 0.09% from the Spearman’s test.

We fit for a power-law correlation in both samples using a Buckley–James (B-J) regression with K-M residuals (a more restrictive EM algorithm fit yields essentially identical results in all cases), and the results are summarized in Table 3 and Figure 2. These regressions make full use of both the detected and censored (upper limit) data. The outer planet sample fit is
consistent with no correlation, the inner sample shows a very significant correlation. In Table 3, we also show the regression analysis results when the X-ray upper limit for system GL 86 is removed from the inner subsample—the change to the correlation is negligible. Our final best fit (including the GL 86 upper limit) to the correlation seen in the inner planet subsample is $L_x = 1.64 \times 10^{28} (M_p \sin i)^{0.59\pm0.03} \text{erg s}^{-1} (1\sigma \text{ errors})$, using the B-J regression. We also note that these results are largely unchanged if we relax the 60 pc distance limit for the sample to include all 271 exoplanet systems (Section 2), or if we exclude systems with $M_p \sin i < 0.1 M_J$.

4. OBSERVATIONAL BIASES

Although a clear, statistically significant, correlation is measured between X-ray luminosity and projected planetary mass for the inner planet subsample—but not for the outer sample—the nature of planet-detection techniques is such that care must be taken to eliminate the possibility of selection biases creating an apparent correlation between observed properties. In particular, RV detection sensitivity is affected by stellar activity. It might also be possible that planet populations at different orbital distances are influenced by the physical environment—giving rise to apparent correlations between planetary and stellar characteristics. This is a recognized problem (e.g., Hartman 2010) and is difficult to resolve. We have made a preliminary investigation of possible biases, described below.

4.1. Jitter and Inclination

We first examine the relationship of the known uncertainties in RV measurements used for planet detection and the measured X-ray luminosity of the stars in our planetary system sample. Residual errors in velocities following the successful fitting of planetary companion orbits are generally reported as rms values. These implicitly include both the systematic instrumental errors (typically a few m s$^{-1}$) and the intrinsic uncertainties due to stellar jitter, a consequence of the finite distribution of velocities in the stellar photosphere due, for example, to convection. We have taken rms values from the primary publications for the most up-to-date RV measurements, quoted in the online Extrasolar Planets Encyclopedia (Schneider 2010). In Figure 3, the detected X-ray luminosity is plotted versus the rms stellar jitter for our complete exoplanet sample, and for just the high-mass ($>0.1 M_J$) inner subsample. As might be expected, the lowest mass planet detections correspond to the lowest rms errors. There is however no apparent correlation between rms errors in RV and stellar X-ray emission detection for the more massive ($>0.1 M_J$) subsample. This suggests that any systematic bias in planet detection introduced by stellar activity (i.e., the preferential detection of only higher mass planets around more active and hence X-ray luminous stars) should be negligible in the bulk of our sample. A potential correlation, or grouping, is seen for the four systems with $M_p \sin i < 0.1 M_J$, which is not unexpected given that the detection of these planets is presently only feasible for the very least active stars. However, any general observational biases against the detection of lower mass planets around more active stars might be expected to affect larger mass planets in the outer sample as well, given the reduced RV signal amplitude with increasing planet–star separation (scaling as $d^{-1/2}$). No such bias is apparent.

The jitter estimates are themselves subject to significant variation. This originates from the specific instruments used to obtain RV spectra (of which there are many, and many “upgrades” spanning the past 15 years of RV planet detection), observing conditions and sampling strategies, and the analysis tools used to obtain the best-fit planetary parameters to the RV curves.

Geometry biases the RV detection of planets to low inclinations with respect to the observer. If coronal X-ray emission due to magnetic field interactions occurs preferentially in localized regions directly between the planet and star (Cuntz
et al. 2000; McIvor et al. 2006; Cohen et al. 2009) this might introduce a systematic trend for higher X-ray emission visibility at low inclinations, which could be correlated with systematically larger estimated planet mass (i.e., larger \( \sin i \)). The presence of this bias would of course itself be evidence for planet–star interaction. This could be tested using a population of transiting systems, where the inclination is known and typically close to \( \sim 90° \), however in the present sample of 29 X-ray detected systems only one (HD 189733) is transiting.

### 4.2. Stellar Rotation

It is well established that main-sequence stellar X-ray luminosity is correlated with stellar rotation rates (Ayres & Linsky 1980; Pallavicini et al. 1981; Maggio et al. 1987) and \( L_x \approx 10^{27}(v_c \sin i)^2 \text{ erg s}^{-1} \) (where \( v_c \sin i \) is in km s\(^{-1}\)) up to a point of saturation at \( L_x/L_{bol} \approx 10^{-3} \). Physically, for slow and intermediate rotation, this relationship has been cast in terms of the Rossby number, \( R_0 = P/\tau_c \), where \( P \) is the rotation period and \( \tau_c \) is the convective turnover time (e.g., see Güdel 2004 and references therein). Saturation then corresponds to \( R_0 < 0.1 \), but which rotation rate this corresponds to decreases with decreasing stellar mass (Pizzolato et al. 2003). For a 1.05 \( M_\odot \) star it is \( P \approx 1.5 \) days, for a 0.7 \( M_\odot \) star it is \( P \approx 3.5 \) days (Güdel 2004). None of the stars in our planet sample appear to reach saturation with \( L_x/L_{bol} \approx 10^{-3} \). Rotation rate is also known to correlate with stellar age—with younger systems exhibiting shorter periods. We note that the three systems with highest \( L_x \) in the inner planet subsample (see also Figure 6) span a range of ages—\( \tau \)-Boo: 2.5 Gyr, HD 162020: 0.76 Gyr, and HD 41004B: 1.6 \( \pm \) 0.8 Gyr (values taken from the literature), and are not exceptionally young.

In Figure 4, we plot the available \( v_c \sin i \) estimates (obtained from the primary data references given in the online exoplanet catalog (Schneider 2010), or alternatively if not available there then from the primary reference given in SIMBAD) versus the \( M_p \sin i \) for both our inner and outer planet X-ray detected subsamples. We note that the stellar inclination need not be the same as that of the planet orbit. As seen with the stellar jitter (Figure 3) the data points corresponding to the lowest mass innermost planets (\( < 0.1 M_\odot \)) appear to group with a lower mean \( v_c \sin i \) than the more massive planet detections. This is consistent with the lower mass planets being more readily detectable in RV data with less line broadening or activity. It therefore seems that the lower X-ray luminosities of the four stars hosting the least massive innermost planets is consistent with the lower rotation rate of these stars, however it is not apparent that this trend is present in the larger mass subset.

At higher masses (> 0.1 \( M_\odot \)) there is no strong correlation, however we note that there may be a division between faster rotating and slower rotating stars. At masses above \( \sim 3 M_\odot \) there may be two groupings of \( v_c \sin i \)—one high at \( \sim 10 \) km s\(^{-1}\) and one low at \( \sim 2–3 \) km s\(^{-1}\). Pont (2009) has recently discussed issues of tidal evolution in close-orbit systems, including the possibility of evolution toward synchronization of the stellar photosphere for \( M_p \approx \sim 3 M_\odot \). It is possible that these present data reflect some of these effects, in the form of “excess” stellar spin due to planetary companions (Lanza 2010).

We further examine the relationship of system X-ray luminosity estimated from the empirical relation \( L_x \approx 10^{27}(v_c \sin i)^2 \text{ erg s}^{-1} \) (see above) to that observed (Figure 5). The original \( L_x \approx 10^{27}(v_c \sin i)^2 \) relation was derived in the Einstein observatory band of 0.2–4 keV. We have therefore converted the predicted luminosities to the 0.1–2.4 keV ROSAT

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**Figure 3.** \( L_x \) is plotted vs. the residual stellar jitter for the complete planet sample with X-ray detections (left panel) and inner planet subsample with \( M_p \sin i > 0.1 M_\odot \) (right panel).

**Figure 4.** Estimated stellar projected rotation velocities \( (v_c \sin i) \) are plotted vs. \( M_p \sin i \) for both inner (filled symbols) and outer (open symbols) planet subsamples.

(A color version of this figure is available in the online journal.)
band assuming the same thermal coronal model as used to convert counts to flux (Section 2) and find $L_x$ \((0.1–2.4) \approx 1.31 \times 10^{27} (v_* \sin i)^2 \text{erg s}^{-1}$.

While there is a general correspondence between the estimated and measured luminosities there is very significant scatter, and for the outer exoplanet subsample there appears to be a systematic underestimate of $L_x$ from stellar rotations.

### 4.3. Planetary Erosion

There is evidence in the literature that suggests the population of planets in short orbits may have been modified by atmospheric erosion (e.g., Lammer et al. 2003). Sanz-Forcada et al. (2010) examine this using the X-ray fluxes at the location of planets in a sample of 59 systems with XMM-Newton, Chandra, and ROSAT X-ray data and claim an excess of lower mass planets in environments of high flux. One explanation could be that atmospheric erosion by high-energy photons has been so efficient that only eroded planets are seen in high flux locations. Other results, examining the relationship of chromospheric activity (via the strengths of Ca H and K lines) to the surface gravitational acceleration computed for transiting planets, do not support this conclusion (Hartman 2010).

However, while erosion may occur, it does not indicate a population bias that would produce the effect seen in our analyses—where the most massive, most closely orbiting planets correspond to the highest coronal emission luminosities (see also Figure 6). It is possible that a further correlation with system age (whereby old systems preferentially harbor the most eroded planets) could reconcile this bias with our results—however (Section 4.2) there is no obvious age-related correlation in our sample. We also note that the majority of X-ray luminosities used by Sanz-Forcada et al. (2010) are derived from pointed X-ray data from Chandra and XMM-Newton with exposure times typically of the order of 10 ks (and do not appear to exclude subgiant stars, e.g., $\gamma$ Cephei). As described in Section 2, such data typically sample only a fraction of orbital phase compared to the RASS, and so while entirely complementary there may be biases introduced that preclude direct comparison.

### 5. TIDAL EFFECTS

For completeness we also examine the relationship between X-ray emission and a scaling parameter proportional to the height of the tidal bulge raised in the stellar atmosphere by a planet at its periastron distance: $M_p/d_{peri}^3$. Projected planet mass is used here. Figure 6 illustrates this distribution. The three systems (labeled) with the largest tidal effect correspond to the three most massive planetary objects in our inner sample, with high $L_x$, suggesting tidal interaction could also play a role. This is broadly consistent with the findings of Pont (2009), where evidence was presented for “excess” stellar rotation due to star–planet tidal torquing in the most extreme cases. These would appear to be excellent targets for future efforts to investigate star–planet interactions.

### 6. INTERPRETATION AND PHYSICAL MODELS

The X-ray luminosities of main-sequence stars containing closely orbiting ($d_{peri} < 0.15$ AU) planets appear to be correlated with the lower limit to planetary mass. The upper limits on X-ray luminosities for planet-harboring systems without X-ray detections are also consistent with this correlation. There is no evidence for this correlation in systems with more distant ($d_{peri} > 0.15$ AU) planets, suggesting that observational selection effects (that might impact low-amplitude RV detections of low-mass planets on short orbits as well as larger mass planets on long orbits) cannot be entirely responsible.

Assuming that this is a consequence of the physical interaction of these planets with their parent stars, then there are two potential forms of the observed correlation. The first is that the X-ray luminosity is entirely governed by the planet–star interaction (which can be excluded on purely energetic and physical grounds, e.g., Lanza 2009), the second is that the X-ray luminosity is a combination of the underlying, or “normal,” coronal
emission, and an additional component due to the planet–star interaction that effectively produces a lower-limit floor to the distribution of luminosities—i.e., a minimum X-ray luminosity that is a function of planet mass. The lack of any statistical evidence for a difference in the mean $L_x$ between our inner and outer subsamples is not inconsistent with planet–star interaction causing a minimum $L_x$ as a function of planet mass. The large range in $L_x$ for main-sequence stars (over at least three orders of magnitude) indicates that a lower $L_x$ limit in close-orbit planet systems may have little effect on the mean emission of a population.

We tentatively examine the hypothesis that the observed $L_x$–mass correlation is a direct consequence of magnetic field interaction between the planets and their host stars that results in the dissipation of energy, some of which results in enhanced X-ray emission from the coronal plasma. No simple predictive model exists for the contribution to coronal emission in this case. Cuntz et al. (2000) make a first-principles estimate of the power of magnetic field interaction between a planet and star, including reconnection due to both the relative motion of a planet and the coronal field and the “steady-state” (i.e., in the case of full stellar synchronization with the planet orbit), due to photospheric motions, field tangling and subsequent reconnection. To zeroth order they suggest that dissipated power scales as $\sim B_p^{2/3}$, where $B_p$ is magnetic field strength at the planet’s poles—with dependencies on stellar field, orbital distance, planet size and factors associated with the magnetospheric radius (interaction point). However, it has been pointed out that magnetic reconnection energy release would not be expected to be sufficient to explain present observational constraints on “hot-spots” in stellar chromospheres due to planet–star interaction (Lanza 2009). Lanza (2009) further suggests that planets can cause a release of built up coronal field energy by dissipating field helicity. In this case, the dissipated power scales as $\sim B_p^{2/3}$ (plus of course a dependency on the stellar magnetic field strength, orbital distance, and other physical parameters). This does, however, assume that magnetic pressure dominates over thermal and ram pressure in the stellar coronal pressure, which may not be valid (Petricec & Russell 1997).

Recent efforts at magnetohydrodynamical (MHD) simulation of star–planet interaction also suggest that total X-ray luminosity can increase (Cohen et al. 2009). However, in this case it is a consequence of localized increases in coronal plasma density due to the interaction, since thermal bremsstrahlung emission scales as plasma density squared. In such models, the net X-ray emission of a star can be enhanced by 10%–30% by even an order of magnitude due to the presence of a close-in planet. This is certainly consistent with our results, however, the simulations span too limited a range of situations at present to allow us to make a quantitative comparison.

Tidal locking (Goldreich & Soter 1966) of inner planets may reduce convectively driven dynamos (e.g., Grießmeier et al. 2004), however induced currents in planetary conductive interiors would sustain planet–star interaction, albeit with a power dissipation efficiency lower by a few orders of magnitude (Lanza 2009).

If we naively assume that the observed correlation of $L_x$ with planet mass in our inner subsample is directly proportional to dissipated power through magnetic field interaction, we can estimate (for example) the ratio of planetary magnetic field strength between 10 $M_J$ and 1 $M_J$ planets. If dissipated power scales as $B_p^{2/3}$ then $(L_x^{10}/L_x^{1})^{3/2} \approx B_p^{10}/B_p^{1} \approx 8^{+19}_{-14}$, implicitly ignoring all errors and scatter due to dependencies on stellar field strengths, age, orbital distance, and other parameters. If the power scaled as $B_p^{2/3}$, we then estimate $(L_x^{10}/L_x^{1})^{3/2} \approx B_p^{10}/B_p^{1} \approx 8^{+19}_{-14}$. If the dissipated power is not directly proportional to the observed $L_x$ variation with planet mass but is rather assumed to go into raising the coronal temperature then since $L_x \propto T^{1/2}$ to first order for a thermal plasma we then estimate (assuming dissipation proportional to $B_p^{2/3}$) that $B_p^{10}/B_p^{1} \sim 64$.

Recent geodynamical modeling work on the origins of magnetic fields has included a proposed scaling law that successfully predicts magnetic field strengths from Earth-mass planets to rapidly rotating low-mass stars (Christensen et al. 2009). This scaling law predicts $B_p^{10}/B_p^{1} = 12^{+3}_{-5}$ (1$\sigma$ uncertainties), which would be in close agreement with our estimate assuming a linear $L_x$ relation to dissipated power going as $B_p^{2/3}$. Interestingly, our higher estimates for this ratio ($\sim 60$) can probably be ruled out, since measured old M-dwarf and T-Tauri star field strengths (Christensen et al. 2009) would then be comparable to that of 10 $M_J$ planets.

7. DISCUSSION

Using a sample of exoplanet host stars, we have examined whether their X-ray emission shows any evidence for energy dissipation due to planet–star interaction. While we find no statistical evidence of enhanced emission for systems harboring the closest-orbit planets (<0.15 AU periapsis distances), we do find evidence for a positive correlation between X-ray luminosity and $M_p \sin i$ that is not seen in systems with more distant known planetary companions. Our analyses include a full treatment of censored data (with detection upper limits) using the tools of survival analysis. We suggest that the observed correlation may represent a lower limit or floor to emission, generated by dissipative (or coronal density enhancement) processes of planet–star magnetic field interaction. Intriguingly, assuming the favored model for dissipated power in planet–star magnetic interaction—scaling as $B_p^{2/3}$—we can crudely estimate the ratio of magnetic field strengths of 10 and 1 $M_J$ planets as $\sim 8^{+19}_{-14}$, which is in remarkably close agreement with the predictions of geodynamical modeling that successfully matches data ranging from planets to stars (Christensen et al. 2009) and suggests a ratio $\sim 12^{+3}_{-5}$. In making this estimate, we relegate several other physically important parameters (orbital radius, stellar magnetic field, coronal magnetic field rotation) to the role of producing scatter—and assume that we nonetheless measure a mean relationship between X-ray luminosity and projected planet mass. Further investigation of this is clearly needed.

We have examined possible observational systematics and selection biases that could produce the observed correlation, or confuse its interpretation. While there is evidence for observational bias due to RV detection sensitivity that results in the lowest projected mass planets in our sample (all with $<0.04$ $M_J$) having stellar parents with lower $L_x$ (all $<5 \times 10^{27}$ erg s$^{-1}$), there is no corresponding evidence for systems with higher mass planets (>0.1 $M_J$). We have also examined the relationship of published data on stellar rotation ($i$, $\sin i$) to both X-ray emission and planet mass. While we see evidence for the stellar hosts of lower mass, close-in, planets ($M_p \sin i < 0.04$ $M_J$) to have systematically slower rotation ($\sim 1$ km s$^{-1}$), there is no clear evidence for any systematic trend in other systems. Again, this indicates—not surprisingly—that the slowest rotating stars allow for the most sensitive RV measurements and therefore enable
the detection of the lowest mass planets. We have also examined the empirically derived relationship between stellar X-ray luminosity and rotation \( L_x \propto (v_s \sin i)^2 \) erg s\(^{-1}\) and observed luminosities and find no obvious indicators that the distribution would influence an apparent \( L_x \propto M_p \sin i \) correlation. We also conclude that planet atmospheric erosion by high-energy photons does not appear to modify populations in the sense that would explain our observed correlation.

Inclination effects could conceivably bias the measurement of planet-stimulated coronal X-ray flux toward systems of low inclination (Section 4.1), with correspondingly larger projected masses. Transiting systems could help resolve this question, however at this time only one system with an observed planetary transit is in the X-ray-detected sample.

8. CONCLUSIONS

The data presented here indicate that X-ray emission from planet-hosting stars may offer a probe of planet–star interactions, and conceivably a probe of the inner workings of close-orbit giant worlds through their convective-dynamo generated magnetic fields. The present sample is however small and more sensitive, targeted, X-ray data on planet hosting stars is needed. These data must also fully sample emission during the entire orbital period in order to avoid biasing any measurements, and conceivably a probe of the inner workings of close-orbit, transiting planet systems over multiple orbital periods and epochs may help disentangle inclination effects, magnetic field dissipation or plasma density enhancement mechanisms, and intrinsic stellar variations.

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8. CONCLUSIONS

The data presented here indicate that X-ray emission from planet-hosting stars may offer a probe of planet–star interactions, and conceivably a probe of the inner workings of close-orbit giant worlds through their convective-dynamo generated magnetic fields. The present sample is however small and more sensitive, targeted, X-ray data on planet hosting stars is needed. These data must also fully sample emission during the entire orbital period in order to avoid biasing any measurement. Current observational programs are beginning to fill this gap (e.g., Popenhaeger et al. 2010; Sanz-Forcada et al. 2010), but sample selection must also be made in a uniform and unbiased fashion in order for these data to be of greatest utility. Given the inherent biases in RV and transit detection of planets, this will be particularly critical.

As present works show (Shkolnik et al. 2008; Walker et al. 2008), it is clear that planet–star interaction in specific cases can directly affect observables at a variety of wavelengths, and that the detailed study of individual objects will also be extremely valuable. In particular, obtaining sensitive time-series X-ray data of close-orbit, transiting planet systems over multiple orbital periods and epochs may help disentangle inclination effects, magnetic field dissipation or plasma density enhancement mechanisms, and intrinsic stellar variations.

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