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Improved Constraints for the XUV Luminosity Evolution of Trappist-1

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ABSTRACT

We re-examine the XUV luminosity evolution of TRAPPIST-1 utilizing new observational constraints of the current stellar parameters (XUV and bolometric luminosity) from multi-epoch X-ray/UV photometry. Following the formalism presented on Fleming et al. (2020), we infer that TRAPPIST-1 maintained a saturated XUV luminosity, relative to the bolometric luminosity, of $\log_{10}(\mathrm{L_{XUV}}/\mathrm{L_{bol}})$ $= -3.03^{+0.25}_{-0.23}$ at early times for a period of $t_{sat}= 3.14^{+2.22}_{-1.46}$ Gyr. After the saturation phase, we find $\mathrm{L_{XUV}}$ decayed over time by an exponential rate of $\beta_{\mathrm{XUV}}= -1.17^{+0.27}_{-0.28}$. Compared to our inferred age of the system, age $= 7.96^{+1.78}_{-1.87}$ Gyr, our result for t_{sat} suggests that there is only a $\sim 4\%$ chance that TRAPPIST-1 still remains in the saturated phase today, which is significantly lower than the previous estimate of 40%. Despite this reduction in t_{sat}, our results remain consistent in the conclusion that the TRAPPIST-1 planets likely received an extreme amount XUV energy—an estimated integrated XUV energy of $\sim 10^{30} - 10^{32}$ erg over the star's lifetime—that is $\sim 15\%$ lower than the original result.

INTRODUCTION

X-ray/extreme ultraviolet (XUV; $\sim 1 - 1000$Å) luminosity is a fundamental aspect of stars, and a key driver for influencing the atmospheric retention and composition of potentially habitable exoplanets (Segura et al. 2010; Luger et al. 2015; Luger & Barnes 2015; Airapetian et al. 2020). One star of particular interest in this regard is TRAPPIST-1, a very late M dwarf orbited by at least 7 planets (Gillon et al. 2016, 2017; Luger et al. 2017), with 3–5 potentially habitable today (Lincowski et al. 2018).

A recent study by Fleming et al. (2020; hereafter F20) inferred the range of evolutionary histories of this star permitted by observations (Wheatley et al. 2017) and the Ribas et al. (2005) empirical model of XUV evolution (Equation 1). The F20 study found that the star is likely still active, with XUV energy representing about 0.1% of the total. After publication, two new data sets (Ducrot et al. 2020; Becker et al. 2020) have become available that could revise the physical properties of the star. Given TRAPPIST-1's prominence in the search for life in the universe, we have re-analyzed the star with the new constraints.

Very late M dwarfs like TRAPPIST-1 are expected to possess an extended initial period of high XUV emission called the "saturated phase" (e.g., West et al. 2008). However, the details of the evolution from saturated phase to more quiescent emission at later times is poorly understood for M dwarfs. Therefore we employ an empirical model derived from observations of FGK stars in which XUV emission (driven by magnetic activity) remains constant relative to the bolometric luminosity for a "saturation time," t_{sat}, and then decreases exponentially afterwards (Ribas et al. 2005):

$$\frac{L_{\mathrm{XUV}}}{L_{\mathrm{bol}}} = \begin{cases} f_{\mathrm{sat}} & t \leq t_{\mathrm{sat}} \\ f_{\mathrm{sat}} \left(\frac{t}{t_{\mathrm{sat}}}\right)^{-\beta_{\mathrm{XUV}}} & t > t_{\mathrm{sat}} \end{cases}, \tag{1}$$

where $\mathrm{L_{bol}}$ is the bolometric luminosity [$\mathrm{L_\odot}$], $\mathrm{L_{XUV}}$ is the XUV luminosity [$\mathrm{L_\odot}$], $f_{\mathrm{sat}} = \log_{10}(\mathrm{L_{XUV}}/\mathrm{L_{bol}})$ is the saturation ratio, t_{sat} is the duration of saturation phase [Gyr], β_{XUV} is the exponential decay rate of $\mathrm{L_{XUV}}$ after saturation, and t is the evolution time [Gyr]. Although limited empirical analysis has been done to explicitly constrain t_{sat} for the lowest mass stars, this model is broadly consistent with measurements of Rossby numbers (which uses rotation period as a proxy for age, $R_o = P_{rot}/\tau$, for convective turnover timescale τ, (Pizzolato et al. 2003)). Furthermore,

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this model was used in F20, so we apply it here as we update their results.

METHODS

Following F20, we use the open-source stellar and planetary system evolution code `VPLanet` (Barnes et al. 2020) to model stellar properties $\mathcal{D}$ as a function of input parameters $\mathbf{x}$. Specifically we use the `STELLAR` module to interpolate evolutionary model grids from Baraffe et al. (2015) to compute bolometric luminosity and the empirical XUV model from Ribas et al. (2005) to compute the XUV luminosity. The posterior probability is computed as $\ln P(x|\mathcal{D}) \propto \ln P(\mathcal{D}|x) + \ln P(x)$, where the input free parameters are $\mathbf{x} = \{m_*,\ \mathrm{f}_{sat},\ t_{sat},\ \mathrm{age},\ \beta_{\mathrm{XUV}}\}$ and m_* denotes the mass $[\mathrm{M}_\odot]$. We keep the prior $\ln P(x)$ consistent with the F20 assumptions, as illustrated in red in Figure 1. We use a Gaussian likelihood $\ln P(\mathcal{D}|x)$ with parameters $\mathcal{D} = \{\mathrm{L}_{\mathrm{bol}},\ \mathrm{L}_{\mathrm{XUV}}\}$, where the bolometric and XUV luminosity of the host star evaluated at the present-day age of the system. The adopted values for the likelihood function are $L_{\mathrm{XUV}} = (1.77 \pm 0.22) \times 10^{-7}\,\mathrm{L}_\odot$ from Becker et al. (2020) and $L_{\mathrm{bol}} = (5.53 \pm 0.19) \times 10^{-4}\,\mathrm{L}_\odot$ from Ducrot et al. (2020).

Additionally we considered adding stellar parameters (particularly the directly measured density) from the transit timing analysis of Agol et al. (2020) into the likelihood function. However in the final results, we chose to omit density (or any density-derived constraints including radius, surface gravity, or effective temperature) in the likelihood, as we found that model densities were inconsistent with observation (likely because late-M dwarf models under-predict stellar radii as F20 noted). We also considered using uniform priors for age, f_{sat}, and β_{XUV}, but found that a lack of informative prior was unable to yield a convergent solution, and hence adopted reasonable Gaussian priors for age, f_{sat}, and β_{XUV} from Burgasser & Mamajek (2017), Wright et al. (2011), and Jackson et al. (2012) respectively.

For computational expedience, we sample the posterior using the approximate Markov chain Monte Carlo (MCMC) framework `approxposterior` (Fleming & VanderPlas 2018), which uses a Gaussian process (GP) surrogate model to estimate $P(x|\mathcal{D})$ from training samples of $\mathbf{x}$. F20 demonstrated that this approach accurately computed the posterior for this model in 980× fewer CPU hours than a standard MCMC method (`emcee`; Foreman-Mackey et al. 2013). Similar to the procedure of F20, we trained the GP on an initial set of 50 `VPLanet` simulations (randomly distributed over the prior space of $\mathbf{x}$). We then iteratively added training sample points, checked the GP convergence after every addition of 100 active-learning sampled training points, and found that the algorithm converged after 23 iterations, or a total of 2,350 training points[1] (see the Appendix of F20 for further details on `approxposterior` configuration, sampling procedure, and convergence criteria).

RESULTS

Our resulting posterior distribution is displayed in Figure 1, which shows that the f_{sat}, t_{sat}, age, and β_{XUV} distributions are all constrained to better precision than in F20. Most significant is the t_{sat} distribution, which is more heavily distributed to younger values, changing the probability that TRAPPIST-1 is still saturated today from 39% in the original result to only 3.7% here. This significant change to t_{sat} results from adopting the $\mathrm{L}_{\mathrm{XUV}}/\mathrm{L}_{\mathrm{bol}}$ value from Becker et al. (2020), which is about a factor of 2 smaller than the value adopted in F20 from Wheatley et al. (2017) and is likely more representative of TRAPPIST-1's quiescent state than the Wheatley et al. (2017) result.

We find that the mass distribution ($m_*= 0.090 \pm 0.001$) is within a $\sim 1\sigma$ agreement with the F20 result ($m_*= 0.089 \pm 0.001$). Despite using an uninformative prior, our mass result is also within a $\sim 1\sigma$ agreement compared to the independent empirical mass-luminosity estimates from Mann et al. (2019) ($m_*= 0.0898 \pm 0.0023$), but with a 2× tighter uncertainty constraint. We note however that our analysis does not account for inherent uncertainties within the stellar evolution models (i.e. it assumes that the Baraffe models perfectly predict the mass-luminosity relationship of a star over time), and does not account for metallicity variation. Thus our model may underestimate the true uncertainty for mass.

Integrating our evolution model over the inferred age of the system for our best fit (median posterior) parameters, we estimate that TRAPPIST-1's planets received total XUV energies of $\sim \{2 \times 10^{32},\ 1 \times 10^{32},\ 3 \times 10^{31},\ 2 \times 10^{31},\ 2 \times 10^{31},\ 1 \times 10^{31},\ 3 \times 10^{30}\}$ erg for planets b–h respectively over their lifetime. This reanalysis suggests the planets have received $\sim 15\%$ less XUV energy than predicted by F20. This change is modest despite the significant change in t_{sat} because most of the XUV luminosity is emitted during the pre-main sequence, and the larger mass that we infer

[1] https://github.com/jbirky/trappist_xuv

results in higher $L_{\rm bol}$ and, hence, higher $L_{\rm XUV}$. Our updated estimates range a factor of $\sim 10-1000\times$ larger than the total XUV energy received by Earth over the Sun's lifetime, which is $\sim 5\times10^{29}$ erg (estimated by the f_{sat}, t_{sat}, and $\beta_{\rm XUV}$ values of solar-type stars from Ribas et al. 2005). Thus, the primary conclusion from F20, that TRAPPIST-1's planets likely received extreme amounts of XUV radiation over their lifetime, remains unchanged.

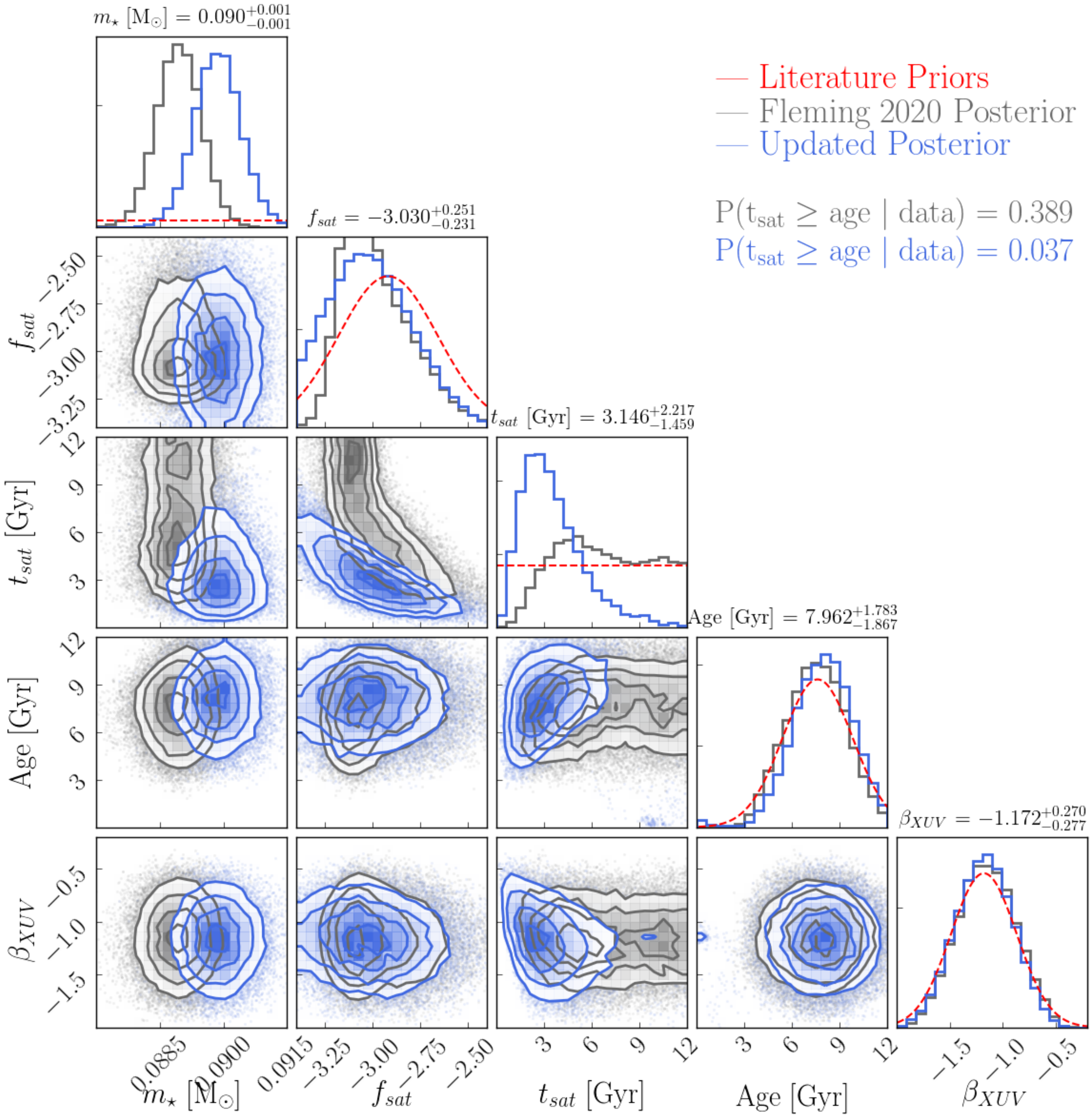

Figure 1. Posterior distribution using updated likelihood L_{XUV} value from Becker et al. (2020) and L_{bol} value from Ducrot et al. (2020) (blue) compared to the posterior from F20 (grey). The prior distributions adopted by both works are shown in red in each histogram panel. Best fit values and uncertainties for each marginal distribution are reported using the medians, 16^{th}, and 84^{th} percentiles. For the full posterior samples, see the repository: https://github.com/jbirky/trappist_xuv

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Software: `VPLanet` (Barnes et al. 2020), `approxposterior` (Fleming & VanderPlas 2018), `emcee`, (Foreman-Mackey et al. 2013), `corner` (Foreman-Mackey 2016)

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