Rate of transient events due to planet-star coalescences

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Abstract

Recent studies (e.g. [1]) demonstrate that planet-star coalescences due to tidal effects can result in flare events observable in optical, UV and soft X-ray bands. Energy release can be as high as $10^{37}-10^{38}$ erg s^{-1} in optics, and up to 10^{36} erg s^{-1} — in EUV/X-ray. This is comparable with nova flares. In our study we use population synthesis approach to estimate the rate of planet-star coalescences in a Milky way-like galaxy. We use mass and initial semimajor axis distributions based on population modelling [2], [3]. We derive type and luminosity distributions of events depending on star and planet parameters. We obtain that in a Milky way-like galaxy frequency of optical transients is $\sim 2.2\cdot10^{-2}$ yr^{-1}, and EUV/X-ray transients $\sim 2.4\cdot10^{-3}$ yr^{-1}. Based on these results we discuss perspectives to detect such events with future instruments.

Types of events

Metzger et al. (2012) [1] distinguish three types of planet-star interactions:

1. "Direct impact" — a planet in-spirals through stellar atmosphere, and is destroyed deeper in the interiors. The critical condition is:
$$a_t < R_* + X_t, \tag{1}$$
where $a_t \approx 2R_*(\bar\rho_*/\bar\rho_{pl})^{1/3}$ is the Roche limit, $X_t \approx 0.7(M_{pl}/M_*)^{1/3}a_t$ — distance from Lagrange L_1 point to the center of the planet, $M_*, R_*, \bar\rho_*$ — stellar mass, radius, and mean density, $M_{pl}, R_{pl}, \bar\rho_{pl}$ — the same three parameters for the planet. Typical light curve of such event is demonstrated in Fig. 1. The peak optical luminosity is:
$$L_{peak} \approx 2\times10^{37}\mathrm{erg/s}\left(\frac{T_{rec}}{6000K}\right)^{4/3}\left(\frac{M_{pl}}{M_{Jup}}\right)^{2/3} \tag{2}$$

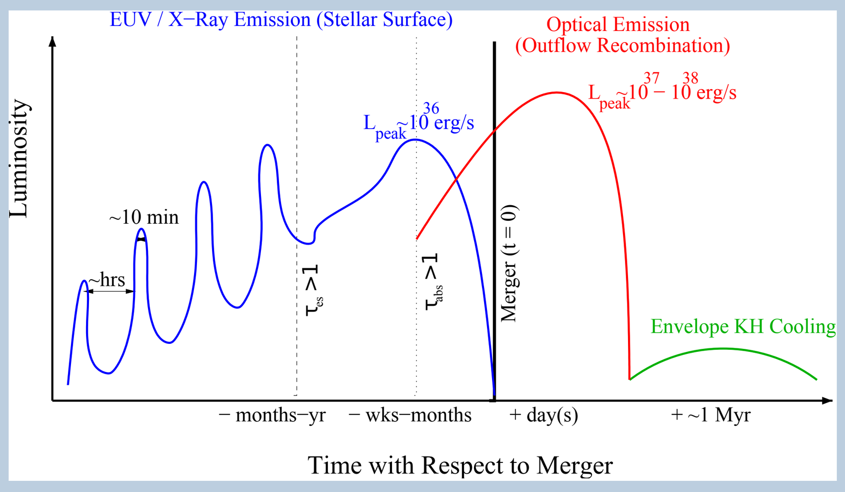

Figure 1: Schematic representation of a light curve of a direct impact of a Jupiter mass planet with a solar mass star (Fig. 7 from [1]).

2. "Tidal disruption" — a planet is destroyed above the stellar surface, and matter forms an accretion disc. This happens if condition (1) is not fulfilled and $\bar\rho_{pl}/\bar\rho_* \gtrsim 1$. For the peak optical luminosity we use results from [1]:
$$L_{peak} \approx 10^{37}\mathrm{erg/s}\left(\frac{M_{pl}}{M_{Jup}}\right) \tag{3}$$
3. Stable mass-transfer from a planet through the inner Lagrange point. This happens if $\bar\rho_{pl}/\bar\rho_* \lesssim 1$. The stellar luminosity is not much increased.

Model: orbital tidal evolution

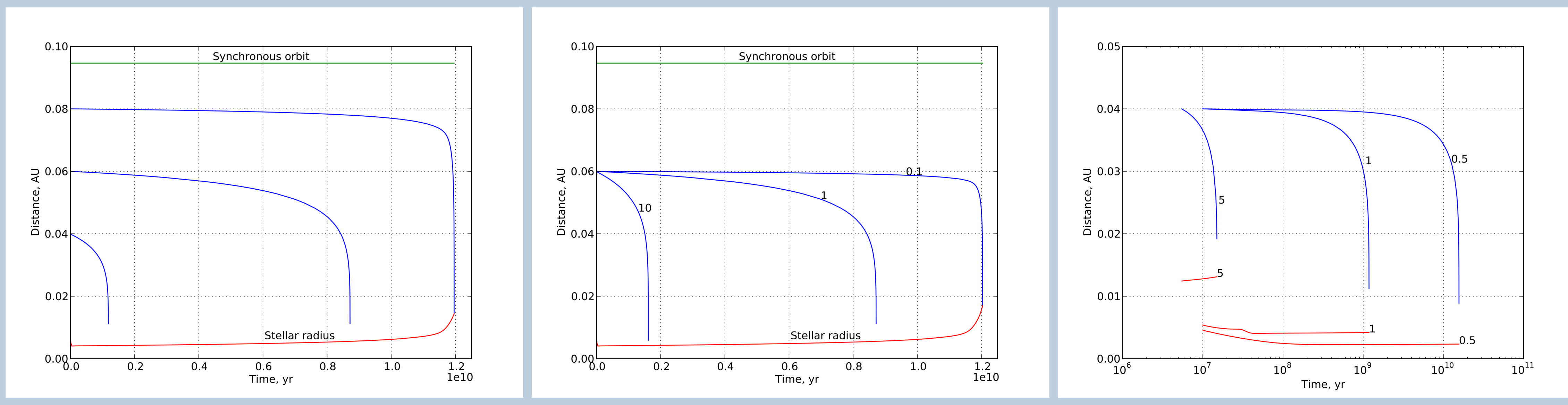

Figure 3: Evolution of orbits for different initial parameters. Left: Stellar mass $1M_\odot$, planet mass $1M_{Jup}$, initial semimajor axis, given in au, is varied. Middle: Stellar mass $1M_\odot$, planet mass, given in $1M_{Jup}$, is varied. Right: Planet mass $1M_{Jup}$, stellar mass, given in $1M_\odot$, is varied. Red lines represent stellar radii taken from evolutionary tracks [5]. Green line corresponds to a synchronous orbit.

In the limit of circular orbits and equilibrium tides the orbital evolution can be described as [4]:
$$\frac{da^{6.5}}{dt} = \mathrm{sign}(a-a_{sync})\frac{117}{4}\sqrt{\frac{G}{M_*}}\frac{R_*^5 M_{pl}}{Q'_*}, \tag{4}$$
where a — semimajor axis, a_{sync} — synchronous orbit size, G — Newton constant, M_* and R_* — stellar mass and radius, M_{pl} — planet mass, $Q'_* = 10^{5.5}$ — modified tidal quality factor. In our calculations M_* and M_{pl} are not changing during evolution, R_* are taken from the set of evolutionary tracks PARSEC V2.1s [5].

Model: population synthesis

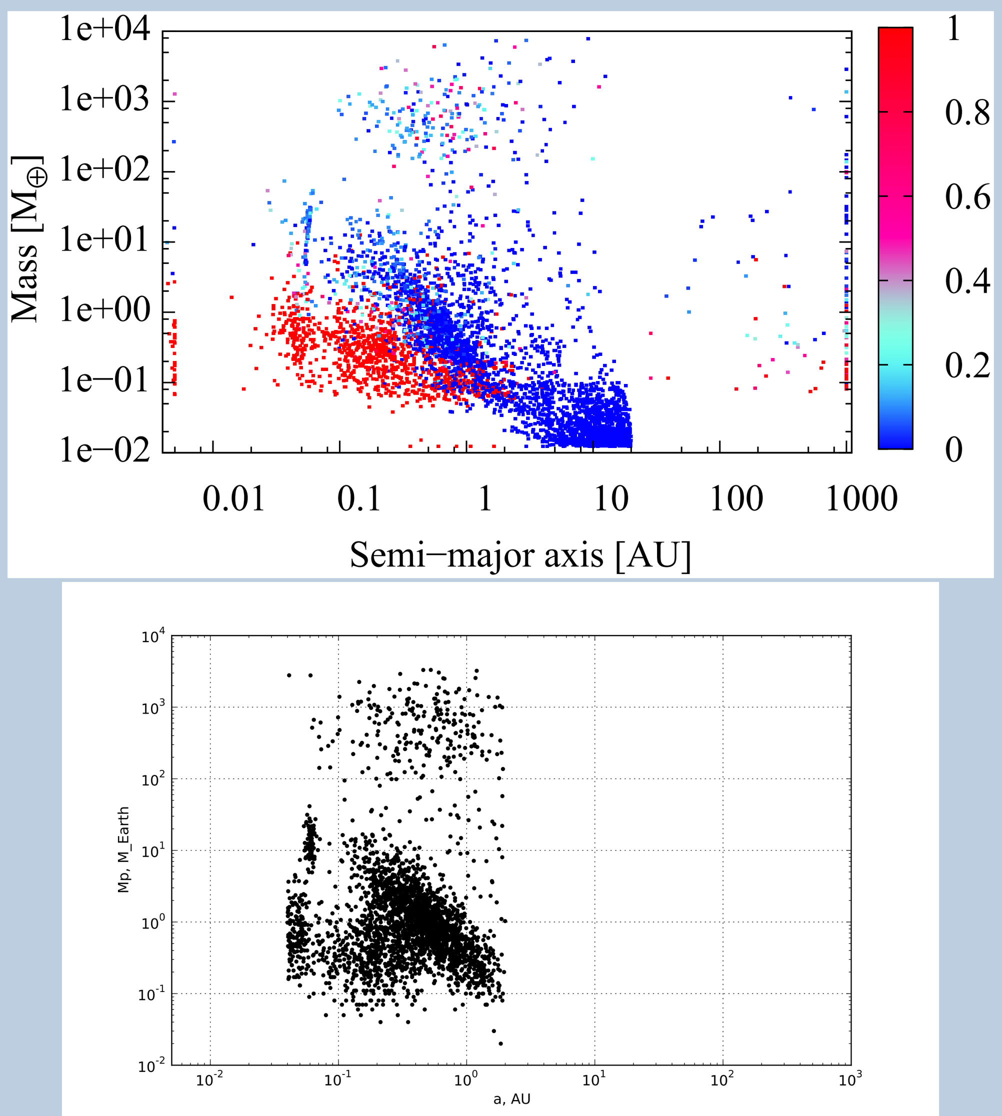

Figure 4: Mass — semimajor axis diagram. Top: results of population synthesis modelling by Alibert et al. (2013) [2]. Down: initial distribution used in our model. We consider planets in the range of initial semimajor axes $0.04 < a < 2$ au.

- **Stellar initial mass function.** Kroupa IMF: $dN/dM_* \sim M_*^{-1.3}$ for $M_* < 0.5M_\odot$ and $dN/dM_* \sim M_*^{-2.3}$ for $M_* > 0.5M_\odot$ [6]. Range of stellar masses: from $0.09M_\odot$ up to $14M_\odot$ (more massive stars have lifetime comparable to the planet formation time scale).
- **Planet mass distribution and initial semimajor axis distribution.** We fitted the M_{pl} - a distribution obtained in [2] (see Fig. 4, upper panel) by several normal distributions (Fig. 4, lower panel). The maximum planet mass is $13M_{Jup}$. Initial semimajor axes cover the range $0.04 < a < 2$ au.
- **Planet systems statistics.** We calculate evolution of 10^7 single planet systems. Then, each systems gets a statistical weight $1/n_{pl}$ depending on the stellar mass. Here n_{pl} is the number of planets in the range $0.04 < a < 2$ au. Coefficients n_{pl} are calculated according to [3]. For the final normalization we use condition $n_{pl}(M_\odot) = 4$.
$$n_{pl}(M_*) = \begin{cases} \left(\frac{M_*}{M_\odot}\right)^{\alpha_D} n_{pl}(M_\odot), & M_* < 1.5M_\odot \quad (\alpha_D = 1.2) \\ 6.5, & M_* \geqslant 1.5M_\odot \end{cases}$$
- **History of starformation.** Star formation rate in the galaxy is taken to be $3M_\odot$/yr during last 7 Gyrs. In the interval 9-7 Gyrs ago it is taken to be zero. And in the previous epoch — $10M_\odot$/yr, see [7].

Results

Planet-star coalescences of all types (direct impact, tidal disruption, and stable mass transfer) can be also divided in two groups depending on the driving mechanism: tidal dissipation (usually valid for main sequence stars) and planet consumption due to stellar expansion on later stages of evolution.

Type of coalecence	Rate, event per year		
	Total	MS stars	Post-MS stars
Direct impact	2.16	$2.2\cdot10^{-2}$	2.14
Tidal disruption	$2.6\cdot10^{-3}$	$2.4\cdot10^{-3}$	$2.1\cdot10^{-4}$
Stable mass transfer	$4.2\cdot10^{-4}$	$3.6\cdot10^{-4}$	$5.8\cdot10^{-5}$

Table 1: Galactic rate of different planet interactions with MS and post-MS stars.

Numbers given for post-MS stars are lower bounds as in our calculations we do not consider planets with $a > 2$ au.
Merger with a planet does not change significantly the luminosity of a giant. Oppositely, direct impact or tidal disruption by a MS star results in a burst. According to the table above in a Milky way-like galaxy for optical transients we have the following rates:

- Direct impacts rate: $\mathbf{2.2\cdot10^{-2}}$ **per yr**
- Tidal disruptions rate: $\mathbf{2.4\cdot10^{-3}}$ **per yr**

Luminosity distribution of optical transients is given in Fig. 2.

Initial stage of a massive planet coalescence with a star (weeks-month prior to the merger) is characterized by quasi-periodically varying EUV/X-ray emission at $E\sim100$ eV and $L_{EUV/X}\lesssim10^{36}$ erg s^{-1}.

- Rate of EUV/X transients in a Milky way-like galaxy: $\mathbf{\sim 2\cdot10^{-3}}$ **per yr**

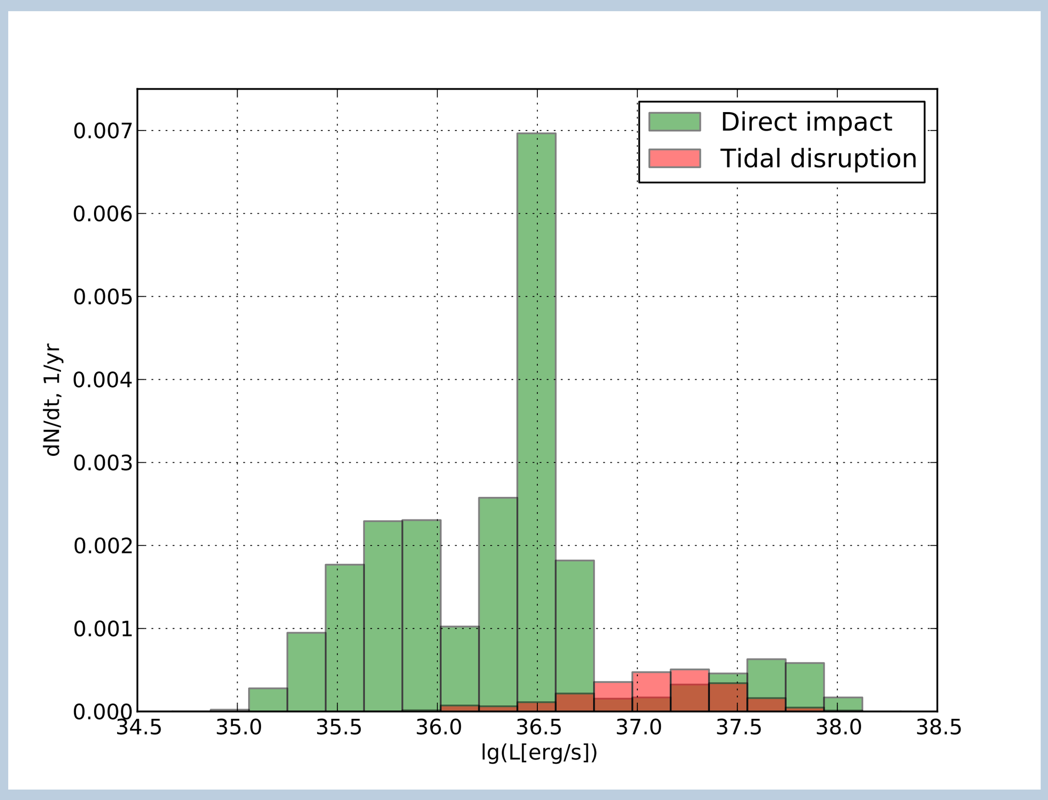

Figure 2: Rate vs. Peak optical luminosity of events for a Milky way-like galaxy.

Most probably, interstellar absorption can exclude detection of significant fraction of events in our Galaxy. Thus, it is necessary to perform surveys of near-by galaxies with large telescopes. In the near future such a program might be realized with the LSST.
Maximum luminosity according to Fig. 2 is $\sim10^{38}$ erg s^{-1}, which corresponds to the absolute magnitude $M_{max} = -6^m$. Then for a source at 1 Mpc we expect visual magnitude $+19^m$, and from 10 Mpc — $+24^m$. According to [1] effective temperature for an optical transient is 5000-7000 K. This corresponds to g band of LSST. Limiting magnitude for a point source in g band is expected to be $+24.8^m$ [9] (due to a galactic background the realistic estimate for a planet-star merger must correspond to a somewhat brighter sources). Thus, LSST can discover such events at distances about few Mpc.

Discussion

It is possible to make a simple estimate for merger rate with MS stars, which is in correspondence with the obtained results. Let the number of MS stars in the galaxy be $N_* = 10^{11.5}$. About 10% among them belong to F, G, K classes. About 1% of F, G, K stars have hot jupiters — massive planets with orbital periods ~1-10 days [8] (this planets make the main contribution to the statistics of observable transients). Then there are about $10^{8.5}$ stars with hot jupiters. If we assume that all planets with periods < 3 days merge during 10-12 Gyrs, and assume the Öpik distribution for initial orbits $f(a)\sim a^{-1}$, we obtain $\sim10^8$ in the life time of a galaxy. If the rate of coalescences is flat, then the present day rate is ~0.01 per yr.
Our numerical results have strong dependence on two model parameters:

1. Initial semimajor axis distribution of massive planets. Position of the internal boundary is very important. If it is shifted towards the star — then the rate of coalescences is significantly enhanced. Also we have to note, that the shape of the distribution we used was obtained for solar mass stars. Variations of the M_{pl} - a distribution (especially for massive planets) for different M_* might modify the results.
2. Tidal evolution. Equilibrium approximation used by us is a very rough one for star-planet systems. Also, the value of Q'_* for different stellar masses and evolutionary stages is not well-known. Different studies show that this parameter can cover wide range of values, and it might be accurately taken in account for robust estimates of star-planet merger rate.

References

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