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Rotation-induced YORP break-up of small bodies to produce post-main-sequence debris

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Abstract

We hypothesize that the in situ break-up of small bodies such as asteroids spun to fission during the giant branch phases of stellar evolution provides an important contribution to the debris orbiting and ultimately polluting white dwarfs. The YORP (Yarkovsky–O'Keefe–Radviesvki–Paddock) effect, which arises from radiation pressure, accelerates the spin rate of asymmetric asteroids, which can eventually shear themselves apart. This pressure is maintained and enhanced around dying stars because the outward push of an asteroid due to stellar mass loss is insignificant compared to the resulting stellar luminosity increase. Consequently, giant star radiation will destroy nearly all bodies with radii in the range 100 m–10 km that survive their parent star's main-sequence lifetime within a distance of about 7 au; smaller bodies are spun apart to their strongest, competent components. This estimate is conservative and would increase for highly asymmetric shapes or incorporation of the inward drag due to giant star stellar wind. The resulting debris field, which could extend to thousands of au, may be perturbed by remnant planetary systems to reproduce the observed dusty and gaseous discs which accompany polluted white dwarfs.

1. Introduction

Asteroids likely represent the primary source of the metal pollution in white dwarf atmospheres. The YORP effect on asteroids has been well-established in the solar system [3], but rarely addressed in other planetary systems. [2] proposes that many asteroids will not survive the giant branch stages of stellar evolution intact due to radiation-induced rotational fission. Consequently, the reservoir of material available to form discs around white dwarfs is composed of smaller fragments than what was previously assumed.

The YORP effect is the rotational acceleration of a body due to the anisotropic absorption and radiation of light. The effect was first proposed in the context of absorbing stellar UV and visible light and the emittance of thermal radiation due to the local heating of the body [1], although the role of conducted heat is now considered possibly as important. Observationally measured rotational acceleration of a number of asteroids has matched predictions from the YORP theory.

The Sun's luminosity will increase by a factor of thousands after it leaves the main sequence, significantly enhancing the YORP effect. Other stars more massive than the Sun will increase their luminosity by greater factors.

2. Figures

In [2], we perform simulations that showcase the extent of rotational disruption when the parent star leaves the main sequence. We assume, conservatively, that all asteroids begin evolving during giant branch evolution without any spin and that the asteroid shape does not change. The eccentricity of the asteroid remains constant, as adiabatic mass-loss predicts. Both the luminosity of the star and the semimajor axis of the asteroid are varied; the latter is varied adiabatically and so is independent of initial orbital orientation. We model the evolution of stars with main-sequence progenitor masses of 1–5 $M_\odot$, as these likely represent the range of progenitor masses which have yielded the vast majority of currently observed white dwarfs.

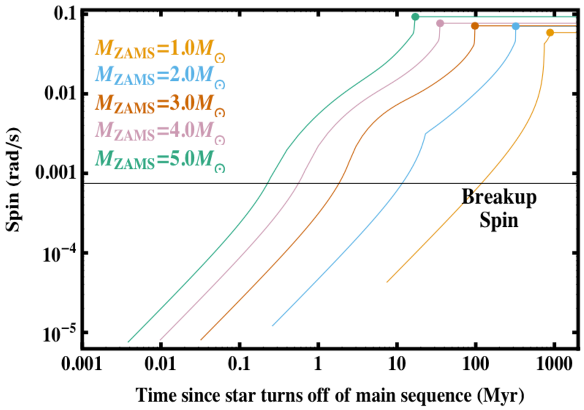

Figure 1: A demonstration of why asteroid belts will be destroyed during giant branch evolution. This plot features the spin-up of objects with radii of R = 1 km, an initial semimajor axis of 7.0 au and an eccentricity of zero. The objects have typical asteroid densities of ρ = 2 g cm^{-3} and a 1% degree of asymmetry. The horizontal black line represents the critical spin value at which an asteroid will tear itself apart. All objects are assumed to begin life on the giant branch with no spin, and the curves are drawn from the beginning of the red giant branch phases. Dots indicate when the stars become white dwarfs. The stars are all assumed to initially harbour Solar metallicity.

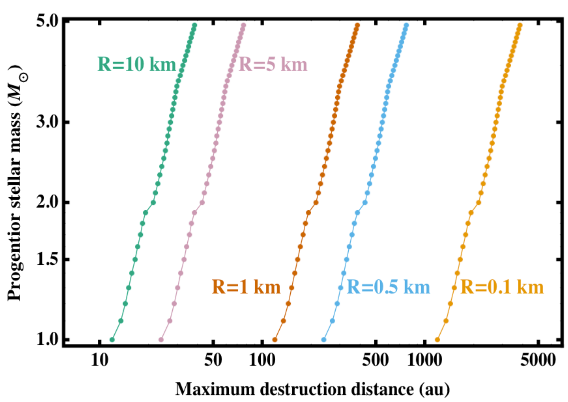

Figure 2: The maximum (final) distance, or semimajor axis, at which asteroids with forever circular orbits, a radius R, density of 2 g cm^{-3} and asymmetry parameter 0.01 can be destroyed by YORP. Each dot represents the result of an integration initilized with the highest initial semimajor axis for which destruction occurs.

3. Conclusions

We have identified a potentially significant source of debris in post-main-sequence planetary systems: the remains of asymmetric asteroids which have spun up beyond their breaking points due to stellar radiation during the giant branch stages of stellar evolution. Typical asymmetric asteroids with radii between about 100 m and 10 km that reside within about 7 au of the star during the main sequence will be destroyed, leaving a debris field orbiting white dwarfs at distances which can range from a few tens to a few thousands of au. Objects larger than 10 km in size will be largely unaffected by YORP. The majority of the asteroidal-based mass would be contained in these large objects, such as analogues of Ceres and Vesta. The debris from rotational break-up may provide a reservoir for white dwarf disc creation and ultimately atmospheric pollution. White dwarf luminosity itself is too low to destroy asteroids in time-scales within Gyr unless the asteroids are already spinning near the break-up speed.

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References

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