Worlds in Migration

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Abstract

In this paper we discuss an alternative track for migration that can explain the existence of Hot Jupiters observed in close orbits around their stars based on a novel interpretation of established work. We also discuss the population of sub-Earth rogue planets that would be created via this migration method, which would be on the order of 2 to 40 billion, many of which would still be present in the Galaxy and potentially detectable.

I. Introduction

In the current era of astronomy, discoveries of exoplanets have become frequent and almost ubiquitous. Though the existence of planets outside our solar system had been discussed as a concept (such as by Bruno (1584) and Struve (1952) to very different results), it was surprising when some of the first planets found differed greatly from our own Solar System’s architecture, particularly as they tended to be Jupiter-like planets orbiting in very close orbits around their host stars [Mayor and Queloz, 1995].

This has naturally led to the challenge to understand how planetary formation processes can have such diversity as to produce not just our own solar system, but the myriad of planetary systems that have now been discovered. While there has been some suggestion that Hot Jupiters are able to form in situ close to their host stars [Batygin et al., 2016], there is also significant evidence that some Hot Jupiters must have migrated inward. Several discovered planets are known to be so close to their host stars that they have high rates of mass loss, such as GJ 3470b [Bourrier et al., 2018], WASP-12b [Hebb et al., 2009; Lammer et al., 2009], and KELT-9b [Gaudi et al., 2017]. Multiple channels have been proposed for how Hot Jupiters migrate inward in their systems, including migration within the gas disk [D’Angelo and Lubow, 2008] or through planet-planet interactions and the Kozai-Lidov mechanism [Kozai, 1962; Lidov, 1962]. These pathways for Hot Jupiter formation have already been compared in great detail [Dawson and Johnson, 2018].

In this paper we propose a renewed consideration of planetary migration as an extension of some ideas initially proposed in Velikovsky (1950), and which despite the criticism that they have received [Goldsmith et al., 1977] may help explain migration as observed in Hot Jupiters when properly considered. We refer to this mechanism as Type V migration.

II. Type V Migration

While Velikovsky (1950) does not present a pathway for Hot Jupiter migration explicitly, his work does outline a mechanism that can be applied to characterize Hot Jupiter migration. Velikovsky presented work on the sudden formation and migration of smaller terrestrial planets on short timescales, on the order of thousands of years. His work specifically focused on limited migration within our own solar system, explaining how electromagnetic forces could cause Venus to be ejected from within Jupiter’s atmosphere before arriving on its current orbit. Velikovsky’s hypothesis was in part based on prior work regarding the formation of new bodies directly from Jupiter’s gaseous body (Hesiod, 700BC).

We instead choose to focus on the influence that such actions would have on Jupiter, or a Jupiter-analogue, rather than on the smaller terrestrial body. The energy loss for the ejection
of a single terrestrial object can be described as a function of the mass and velocity of the departing object:

$$\Delta E = \frac{1}{2} M_\oplus v^2$$

(1)

Due to the scope of this work we fix $M_\oplus$ at 1 Venusian mass, or 0.815 $M_\oplus$ (Konopliv et al., 1999). The velocity at time of ejection is slightly more complex problem. We examine three different velocities, 100 km/s, 300 km/s, and 1000 km/s, the first two representing the velocities of most stars in the Milky Way, with the last being typical of a hypervelocity star (Boubert et al., 2017; Hills, 1988). Note that this velocity is combined with the escape velocities necessary for both escaping the mass of the Jovian planet and the host star (as 1 $M_\star$ in this work) and can be expressed using the equation for escape velocity:

$$V_{\text{esc}} = \sqrt{\frac{2GM_\star}{r}}$$

(2)

Here the mass in question is of the primary object, and $r$ represents the Jovian planetary radius or the orbital radius of the Jovian planet for escape velocities from the planet and from the star respectively. We treat the Jovian radius as $1R_J$ for our purposes. These energy calculations neglect relativistic effects (Einstein, 1905).

By using the change in energy as calculated by (1) we can then determine how the orbital radius of the planet, in turn, changes by calculating the new orbital radius as a function of $\Delta E$, $M_{\text{planet}}$, $M_\star$, and the current orbital radius, as given in Eq.3

$$r_2 = \frac{1}{r_1} \frac{\Delta E}{GM_{\text{planet}}M_\star}$$

(3)

III. Simulations

In order to simulate the impact that Type V migration can have on a Jovian planet, we carry out a suite of planetary migration simulations. Our simulations use a range of Jovian planets between 2 and 8 $M_J$, all of which we place at a distance of 5 AU initially (Jewitt et al., 2007). We then eject 500 Venusian-mass planets with the three different final velocities mentioned in II, tracking how the planetary mass and orbital radius change, as shown in Figure I.

Our results show that it is quite possible that a Jovian-mass planet can lose sufficient mass and energy to migrate inward to the semi-major axis regime of Hot Jupiters while still maintaining sufficient mass to fit our observations. In the case of a 2$M_J$ planet, all tracks reach our final semi-major axis goal of 0.05 AU, with the slowest process requiring somewhat over 100 ejections. Alternatively, the hypervelocity ejections require fewer than 10 ejections from the 2$M_J$ planet to migrate to a 0.05 AU orbital radius. Even in the high-mass case of 8$M_J$, the 0.05 AU distance is reached for all tracks, although this does require more ejection events.

IV. Discussion

The natural product of this Type V migration channel is a Galactic population of rogue planets. The existence of such planets has been discussed in several prior works, including some discussion of the dynamical histories required to create them (Bear, 2000; Lissauer, 1987; Laughlin and Adams, 2000). Type V migration necessitates that the Jovian planet remains in the system and only the terrestrial planet is actually ejected. Therefore, our described Type V migration mechanism is consistent with more recent microlensing observations that have found that while there are not many large rogue planets, there may be a large number of terrestrial-sized rogue exoplanets within the Milky Way (Mróz et al., 2017). These ejected planets fall well within the sensitivity range of the upcoming Wide-Field InfraRed Survey Telescope (WFIRST) microlensing mission (Gehrels et al., 2015), which will be sensitive to planets down to the size of Ganymede (Penny et al., 2019).

The estimated fraction of stars that host Hot Jupiters is around 1% (Wang et al., 2015). With roughly 20 billion roughly sun-like stars
Figure 1: The orbital radius of a Jovian planet as a function of remaining planetary mass for a range of initial planetary masses. For each initial planetary mass we examine three different tracks (as indicated by the symbols) that correspond to the resulting velocity of the ejected Venusian-mass bodies. The markers after the initial mass represent Jovian mass-loss corresponding to 10, 50, 100, 250, and 500 Venusian masses. Our starting point at the snow line is the red solid line at 5 AU, and the end point of 0.05 AU is the red dashed line.

in the galaxy (Plait 2013), this translates to 200 million Hot Jupiters. Given the number of terrestrial planet ejections needed to generate this number of Hot Jupiters, our simulations suggest a population of 2-40 billion rogue Venu-sians in the Galaxy. We note, however, that if a significant fraction of these ejections involve hypervelocity planets, then the number still in the galaxy may be notably reduced as these bodies would be traveling in excess of galactic escape velocities, and so could become intergalactic planetary bodies (Beastie Boys 1998).

While their fates have not been the primary focus of this work, these rogue Venusians (which have been speculated upon in previous works (Lovecraft and Sterling 1939; Heinlein 1951; Sterling 1961; Adamski and Leslie 1977)) would also be prime candidates for Steppenwolf planets (Abbot and Switzer 2011), since they constitute a population of smaller terrestrial planets with thick insulating atmospheres that may be much more hospitable when not subject to the high irradiation that Venus receives.

V. Summary

In this paper we have proposed that the work of Velikovsky should be revisited in terms of how the ejection of small terrestrial planets from gas giants may provide an alternative migration track that can explain the observed population of Hot Jupiters. This would additionally indicate a population of rogue Venusian exoplanets numbering between 2 and 40 billion that may be detected by future microlensing missions such as WFIRST.

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1http://www.astropy.org
for Astronomy (Astropy Collaboration et al., 2013) [Price-Whelan et al., 2018].

REFERENCES

Abbot, D. S. and Switzer, E. R. (2011). The Steppewolf: A Proposal for a Habitable Planet in Interstellar Space. ApJ, 735:L27.

Adamski, G. and Leslie, D. (1977). Flying Saucers Have Landed. CreateSpace Independent Publishing Platform.

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. (2013). Astropy: A community Python package for astronomy. A&A, 558:A33.

Batygin, K., Bodenheimer, P. H., and Laughlin, G. P. (2016). In Situ Formation and Dynamical Evolution of Hot Jupiter Systems. ApJ, 829:114.

Bear, G. (2000). Rogue Planet. Del Rey Books.

Beastie Boys (1998). Intergalactic. Hello Nasty.

Boubert, D., Erkal, D., Evans, N. W., and Izard, R. G. (2017). Hypervelocity runaways from the Large Magellanic Cloud. MNRAS, 469:2151–2162.

Bourrier, V., Lecavelier des Etangs, A., Ehrenreich, D., et al. (2018). Hubble PanCET: an extended upper atmosphere of neutral hydrogen around the warm Neptune GJ 3470b. A&A, 620:A147.

Bruno, G. (1584). De l’infinito universo e mondi.

D’Angelo, G. and Lubow, S. H. (2008). Evolution of Migrating Planets Undergoing Gas Accretion. ApJ, 685:560–583.

Dawson, R. I. and Johnson, J. A. (2018). Origins of Hot Jupiters. Annual Review of Astronomy and Astrophysics, 56:175–221.

Einstein, A. (1905). Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig? Annalen der Physik, 323:639–641.

Gaudi, B. S., Stassun, K. G., Collins, K. A., et al. (2017). A giant planet undergoing extreme-ultraviolet irradiation by its hot massive-star host. Nature, 546:514–518.

Gehrels, N., Spergel, D., and WFIRST SDT Project (2015). Wide-Field InfraRed Survey Telescope (WFIRST) Mission and Synergies with LISA and LIGO-Virgo. In Journal of Physics Conference Series, volume 610 of Journal of Physics Conference Series, page 012007.

Goldsmith, D., Storer, C., Sagan, C., Mulholland, J., Huber, P., and Morrison, D. (1977). Scientists Confront Velikovsky. Cornell University Press.

Hebb, L., Collier-Cameron, A., Loeillet, B., et al. (2009). WASP-12b: The Hottest Transiting Extrasolar Planet Yet Discovered. ApJ, 693:1920–1928.

Heinlein, R. (1951). Between Planets. Charles Scribner’s Sons.

Hesiod (circa 700 BC). Theogony.

Hills, J. G. (1988). Hyper-velocity and tidal stars from binaries disrupted by a massive Galactic black hole. Nature, 331:687–689.

Jewitt, D., Chizmadia, L., Grimm, R., and Prialnik, D. (2007). Water in the Small Bodies of the Solar System. Protostars and Planets V, pages 863–878.

Konopliv, A. S., Banerdt, W. B., and Sjogren, W. L. (1999). Venus Gravity: 180th Degree and Order Model. Icarus, 139:3–18.

Kozai, Y. (1962). Secular perturbations of asteroids with high inclination and eccentricity. AJ, 67:591.

Lammer, H., Odert, P., Leitzinger, M., et al. (2009). Determining the mass loss limit for close-in exoplanets: what can we learn from transit observations? A&A, 506:399–410.

Laughlin, G. and Adams, F. C. (2000). The Frozen Earth: Binary Scattering Events and the Fate of the Solar System. Icarus, 145:614–627.
Lidov, M. L. (1962). The evolution of orbits of artificial satellites of planets under the action of gravitational perturbations of external bodies. Planet. Space Sci., 9:719–759.

Lissauer, J. J. (1987). Timescales for planetary accretion and the structure of the protoplanetary disk. Icarus, 69:249–265.

Lovecraft, H. and Sterling, K. (1939). In the Walls of Eryx. Weird Stories.

Mayor, M. and Queloz, D. (1995). A Jupiter-mass companion to a solar-type star. Nature, 378:355–359.

Mróz, P., Udalski, A., Skowron, J., et al. (2017). No large population of unbound or wide-orbit Jupiter-mass planets. Nature, 548:183–186.

Penny, M. T., Gaudi, B. S., Kerins, E., et al. (2019). Predictions of the WFIRST Microlensing Survey. I. Bound Planet Detection Rates. The Astrophysical Journal Supplement Series, 241:3.

Plait, P. (2013). The Sky May Be Filled with Earth-like Planets. Slate.

Price-Whelan, A. M., Sipőcz, B. M., Günther, H. M., et al. (2018). The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. AJ, 156:123.

Sterling, R. (1961). Will the real martian please stand up? Twilight Zone, 2(28).

Struve, O. (1952). Proposal for a project of high-precision stellar radial velocity work. The Observatory, 72:199–200.

Velikovsky, I. (1950). Worlds in Collision. Macmillan Publishers.

Wang, J., Fischer, D. A., Horch, E. P., and Huang, X. (2015). On the Occurrence Rate of Hot Jupiters in Different Stellar Environments. ApJ, 799:229.