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**Introduction:**  Volatile escape is the classic existential problem of planetary atmospheres. The problem has gained new currency now that we can study the cumulative effects of escape from extrasolar planets. Escape itself is likely to be a rapid process, relatively unlikely to be caught in the act, but the cumulative effects of escape – in particular, the distinction between planets with and without atmospheres – should show up in the statistics of the new planets.

The new planets make a moving target.  It can be difficult to keep up, and every day the paper boy brings more.  Of course most of these will be giant planets loosely resembling Saturn or Neptune albeit hotter and nearer their stars, as big hot fast-orbiting exoplanets are the least exceedingly difficult to discover.  But they are still planets, all in all, and although twenty years ago experts could prove on general principles that they did not exist, we have come round rather quickly, and they should be welcome now at LPSC.

Here we will discuss the empirical division between planets with and without atmospheres. For most exoplanets the question of whether a planet has or has not an atmosphere is a fuzzy inference based on the planet's bulk density. A probably safe presumption is that a low density planet is one with abundant volatiles, in the general mold of Saturn or Neptune.  On the other hand a high density low mass planet could be volatile-poor, in the general mold of Earth or Mercury. We will focus on planets, mostly seen in transit, for which both radius and mass are measured, as these are the planets with measured densities.  More could be said: a lot of subtle recent work has been devoted to determining the composition of planets from equations of state or directly observing atmospheres in transit, but we will not go there.

What interests us here is that, from the first, the transiting extrasolar planets appear to have fit into a pattern already seen in our own Solar System, as shown in Fig. 1.  We first noticed this in 2004 when there were just two transiting exoplanets to consider. The trend was well-defined by late 2007. Figure 1 shows how matters stood in Dec 2012 with ~240 exoplanets. The figure shows that the boundary between planets with and without active volatiles – the cosmic shoreline, as it were – is both well-defined and follows a power law.

Figure 1 plots insolation vs. escape velocity for a reasonably comprehensive sample of planets and satellites in our own Solar System.  These are the quantities one would plot if one wishes to compare the radiative infuence of the central star to the gravitational well that holds the volatiles to the planet.  (In a companion abstract we plot impact velocity vs. escape velocity for the same planets.  These are the quantities one plots if if one wishes to assess the role of impact erosion, as impact velocity is a good proxy for the specific energy delivered by impacts.)

In Fig 1 the presence or absence of an atmosphere is indicated by filled or open symbols, respectively. For the worlds of our Solar System, what is meant by "having an atmosphere" is usually pretty obvious, but there are borderline cases (such as Io, which has a very thin volcanogenic atmosphere, or Chiron, which is basically a big comet in an unstable orbit) that complicate matters.  The main complication here is with the Kuiper Belt Objects, a few of the largest of which retain stores of frozen methane on their surfaces.  These are plotted in purple on Fig 1 as boxes-half-full. The presumption is that their surface volatiles will evaporate when close to the Sun and they will then for a time have atmospheres similar to those of Pluto and Triton. This sort of seasonal transformation is very likely for Eris, which is currently near aphelion, and rather unlikely for Sedna, which is rather near its perihelion.

Also plotted on Fig 1 is the known roster of extrasolar transiting planets as of December 2012. For these planets, orbital parameters, diameters, and stellar luminosities are measured.  It is straightforward to convert these measured properties into escape velocities and irradiations.  A few other well-characterized exoplanets, such as the directly imaged planets of HD8799, are also plotted. For most of the exoplanets the measured diameters and densities are typical of giant planets, which indicates that the transiting planets plotted on Fig 1 have atmospheres.

The general pattern seen in Fig 1 is what one would expect to see if escape were the most important process governing the volatile inventories of planets. Where the gravitational well is deep (measured by escape velocity), or where the eroding efforts of the central sun are feeble (measured here by insolation), planetary atmospheres are thick.  Where the gravity is weak or the sun too bright, there are only airless planets.

What Fig 1 does not show is what one might expect to see if the presence of atmospheres depended mostly on temperature or volatile supply.  To put this another way, small warm worlds with significant atmospheres are missing.  Such worlds are permitted if not manda-

tory in supply-side scenarios; indeed, active comets provide extreme examples of what such worlds can look like during their brief lives.

Figure 1 also reveals two notable surprises. The first is that the lesser planets in our Solar System with atmospheres seem to be strung out along a line, rather than scattered over the half-space below and to the right of the bounding line. The second surprise is that the known transiting extrasolar giant planets crowd against the extrapolation of that line.

The five orange symbols represent planets that plot to the left and above the cosmic shoreline. They are disobedient, and if they possessed thick atmospheres they would challenge our hypothesis. However, all five exceptions are quite dense. The three most exceptional are marked and characterized explicitly on the plot. We had been concerned about 55 Cnc e, which according to the online Exoplanet Encyclopedia had a density of only 4.5 g/cm$^3$, which if correct would pose a considerable challenge to our thinking, but newer information revises the density up to 5.9 g/cm$^3$, which is in the range expected of a purely iron-silicate body.

(Two other exoplanets - KOI 55 b and KOI 55c - lie far above the bounds of this graph. These are interesting but peculiar worlds. The star KOI 55 is a hot blue subdwarf. It has already evolved through a red giant phase and is now becoming a white dwarf. The planets are very close to the star and very hot – of order 7000 K. They are a bit smaller and slightly denser than Earth, and presumably their atmospheres are made of silicates and metals.)

The labeled curves represent simple models. The black curve labeled CH$_4$ is the evaporation line for methane planets. What it plots specifically is the line below which a planet composed of methane would endure for more than 5 billion years. It provides a good first approximation to the presence of methane in the solar system. The light blue curves are the comparable evaporation lines for H$_2$O. It is curious that the water-line should coincide with the asteroid belt, but the water line does not provide the same guidance to planets that the methane line does for KBOs. The green curve – the H$_2$ line – may have relevance to the terrestrial planets.

The exoplanets are compared to two simple models, one an EUV-fueled energy-limited escape model with tidal truncation of the same general form as one may find in a dozen papers in the astrophysical literature, and the other a more idiosyncratic model of global thermal instability of a jovian planet.

To first approximation the dividing line on Figure 1 can be described by $I \propto v_{esc}^4$. The line spans two orders of magnitude in escape velocity and nearly eight orders of magnitude in insolation. It is remarkable that a power law should relate hot jupiters at one extreme to Pluto and Triton at the other.

Energy-limited escape may not be the answer. If we compare stellar radiation intercepted to the power required to raise the atmosphere out of the planet's gravitation well, we have $I R^2 \propto GM\dot{M}/R$. If we write $\dot{M} = M/\tau$, we obtain $I \propto v_{esc}^4/R\tau$, which has too much $R$ in it. Planetary radii on Fig 1 span two orders of magnitude, which could spoil the power law.

A different argument begins from Hunten's rule of thumb, which is that thermal escape is expected if $H/R > 1/6$. This implies that $T \propto \mu g R \rightarrow T \propto \mu v_{exc}^2$. Fig 1 suggests that the mean molecular weight is important. It is likely that mean molecular weight depends on temperature. At 100 K, the atmosphere may be N$_2$; at 350 K, H$_2$O; at 1500 K, H$_2$; at 3000 K, H; at 8000 K, H$^+$ and e$^-$. If we approximate $\mu \propto T^{-1}$, we then obtain $T^2 \propto v_{esc}^2 \rightarrow I \propto T^4 \propto v_{esc}^4$, as observed.
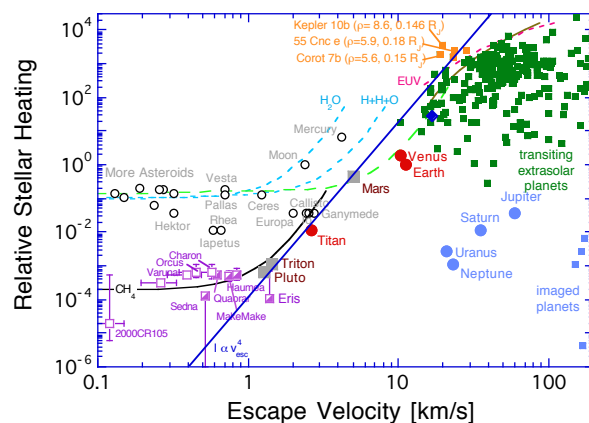


**Figure 1.** Atmospheres are found where gravitational binding energy is high and solar heating low. This is shown here by plotting escape velocity against insolation for the fully characterized planets. The presence or absence of an atmosphere is indicated by filled or open symbols, respectively. Extrasolar planets with known masses and radii as of December 2012 (http://exoplanet.eu, obvious typos corrected) are also plotted. Most of these have been detected in transit. In general the green planets are big and therefore hydrogen-rich. Some simple models of planetary mass loss are shown as curves; these are discussed somewhat in the text. The $I \propto v_{esc}^4$ power law is drawn in blue. The orange planets disobey the master power law, but these are the exceptions to prove the rule: they are dense enough that they give no compelling reason to think that they retain atmospheres.