What is transiting HD 139139?

Jean Schneider
Paris Observatory

The NASA mission Kepler has detected 28 transits with depths $\eta \approx 220$ ppm and durations $D_T \approx 2.5$ hours in the light curve of HD139139 (radius $R_* = 1.14 R_\odot$, $M_* = 1 M_\odot$ and $d_* = 100$ pc) during a 87 days campaign. Their arrival times are erratic. Rappaport et al. (2019) discard ten explanations. It is not clear if the transits are for HD 139139 or for a star B at 3.3". New radial velocity variation data give $RV < 10 \text{m/s}$ for HD139139 in 4 days (F. Bouchy and S. Udry, private communication) excluding a close-in $M = 50 M_Jup$ planet orbiting HD 139139, as proposed earlier (Schneider 2019). (However, this explanation is still valid for the star B for which radial velocity data are very poor).

Here I thus explore new tentative explanations and their likelihood: 1/ An eccentric transiter's belt 2/ Interstellar transiter 3/ Solar System objects.

I consider cases where there are several objects transiting the star HD 139139. Details are in preparation. As a general constraint, any transiter must have an orbital period larger than $87/2 = 43$ days to avoid 3 transits with equal interarrival times in 87 days. Since a transiter can make only two transits in 87 days, there are $28/2 = 14$ transitors.

1 Eccentric transiter's belt

Objects transiting HD139139 at the periastron of an orbit with an orbital period $P_T$ and an eccentricity $e$ give a mean transit duration

$$D_T = \sqrt{3} R_* \sqrt{\frac{1 - e}{1 + e}} \left[ \frac{2 \pi P_T}{GM_*} \right]^{1/3}$$

Several objects randomly distributed on an asteroid-like belt give random transit arrival times. From equation (1)

$$e = \frac{\left( 1 - D_T^2 GM_/a_T^2 R_*^2 \right)}{\left( 1 + D_T^2 GM_/a_T^2 R_*^2 \right)}$$

To have $D_T = 2.5$ hours, $e$ must be 0.74 for a 43 days orbit. For a belt of trojan objects with an azimuthal distribution of 40° similar to Solar System trojans (Figure 1a), the orbital period must be 87 days $\times 40^\circ/360^\circ = 783$ days, leading to an eccentricity of 0.95 (for comparison, $e=0.97$ for HD 20782b). According to Lyra et al. (2009), trojan objects can have several Earth masses.

---

Figure 1

Four configurations of transiter's
The transits should then disappear when the trojan belt is not transiting and reappear after a time \( P_T(80^\circ/360^\circ) \) or \( P_T(200^\circ/360^\circ) \). However, one then faces stability problems making this configuration less likely.

2 Interstellar objects
Transiters at rest at a distance \( d_T \ll d_* \) give a transit duration, due to the Earth velocity \( V_\oplus \) around the Sun, of \( D_T = d_T \times 2 R_\oplus / V_\oplus \), or \( D_T = D_{T_\oplus} V_\oplus / 2 R_\oplus \) (Figure 1b). For a 2.5 hour transit \( d_T = 20 \text{ pc} \). Then the 220 ppm depth gives a radius of \( \sqrt{\eta} R_\oplus d_T / d_* = 0.3 R_\oplus \), or a mass of \( 0.02 M_\oplus \). The group of objects can either be a series of objects orbiting a non-transiting faint star or brown dwarf, or a self-gravitating spherical cluster similar to stellar globular clusters. However, in the latter case one would have to explain its formation. If the group of objects has a typical velocity of 20 km/s, the numbers remain the same within a factor 2.

Suppose that, according to the virial theorem to maintain its stability, the cluster of transiters has the same velocity dispersion \( \sqrt{GM_{cl}}/r_c \approx 2 \text{ km/s} \) (where \( M_{cl} \) is its total mass), as a typical stellar globular cluster (Meylan & Heggie 1997).

Then with a core radius of \( r_c = 0.5 \times 87 \text{ days} / V_\oplus = 1.5 \text{ AU} \), the total mass of the cluster of transiters should be \( 10^{-2} M_\oplus \). The mass of each transiter being \(~20^{-2} M_\oplus \), the cluster should contain \(~3 \times 10^5 \) objects.

For a core radius of \( r_c \) of 1.5 AU, the projected interdistance of objects is \( r_c / (210^8)^{1/3} \approx 5 R_\oplus \). The interarrival time of transits then is \( 5 R_\oplus / V_\oplus = 2.5 \times 10^7 \text{ sec} \), in agreement with the observed mean interarrival times of 3 days.

3 Solar System objects
Let us take objects at a distance \( d_T = 500 \text{ AU} \) or more. Then their size \( r_T \) is \( \sqrt{\eta} R_\oplus d_T / d_* = 17 \text{ m} \). Their orbital velocity around the Sun, at more than 500 AU, is less than 1.3 km/s.

The duration \( D_T \) of their transits is thus dominated by the Earth velocity on its orbit around the Sun: \( D_T = 2 R_\oplus (d_T / d_*) / V_\oplus \). For \( d_T = 500 \text{ AU} \), the duration is 12 sec, incompatible with the observed 2.5 h duration.

But one can assume that there is some source of extra high velocity \( V_T \) of each of these objects which compensates the Earth velocity (Figure 1c).

After some algebra one finds that (since \( d_T \ll d_* \)) the transverse velocity of transiters is

\[ V_T = V_\oplus - 2 d_T R_\oplus / (d_* \times 2 \text{ hours}) \approx 30 - \epsilon \text{ km/s} \]

(where \( \epsilon = 2 d_T R_* / (D_T V_\oplus d_T) \) is negligible compared to 30 km/s).

Suppose a configuration where there is a group of transiters. Then, since there are transits during 87 days at least, this group, supposed to have a group orbital velocity \( V_G \) around the Sun of 1.3 km/s at 500 AU, must have a transverse extension \( a_T = 87 \text{ days} \times V_G = 0.065 \text{ AU} \) at least.

As a concrete model, these objects could be in a ring of \(~17 \text{ m} \) rocks around a massive, yet unseen, planet at \( > 500 \text{ AU} \) (Figure 1d). For circular orbits around a planet, to have a velocity of \(~30 \text{ km/s} \) for the transiters \(^1\) at \( a_T = 0.03 \text{ AU} \) around their parent planet, the latter must have a mass of 30 Jupiter masses (Figure 1d).

Or the transiters could presently be at the perihelion of an orbit with an eccentricity \( e \). To have a velocity of 30 km/s with a semi-major axis of 500 AU, from equation (2), \( e \) must be 0.9998, similar to the orbit of the comet C/1680 V1 (semi-major axis 444 AU, eccentricity 0.999996). Since one

\(^1\) To be more precise, the velocity then is \( 30 \text{ km/s} \times \cos \omega \) where \( \omega \) is a random orbital phase factor around the planet; it leads to the observed dispersion of transit durations. I skip this discussion here.
must have at least $28/2 = 14$ transiters, they could be the result of a disrupted comet or asteroid by collision with an interstellar asteroid entering the Solar System (Couture 2019, Moro-Martin et al. 2009).

Finally, we clearly need more data (more transits, radial velocities and imaging).

**Acknowledgement**
I thank Valéry Lainey for discussions.

**References**
Couture G., 2019. *Astron. J.*, submitted, arxiv:1908.06191

Lyra W. et al. 2009. *Astron. & Astrophys.* 493. 1125

Meylan G. & Heggie D. 1997. *Rev.* 8, 1

Moro-Martin A. et al. 2009. *ApJ.* 704, 733

Rappaport S. et al. 2019. *MNRAS,* 488, 2455

Schneider J. 2019. *RNAAS* 3, 108