X-RAY, UV, OPTICAL IRRADIANCES AND AGE OF BARNARD'S STAR'S NEW SUPER-EARTH PLANET:—"CAN LIFE FIND A WAY" ON A COLD PLANET?

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Introduction and Background

Barnard's Star (GJ 699; V = +9.51 mag) is a dim, old red dwarf (M3.5 V). At 6 LY it is the 2nd nearest star system. Until recently, Barnard's Star's claim to stardom is having the largest proper motion (mu = 10.4"/yr). Recently adding to its fame, Ribas et al. (2018 *Nature 563, 365*) discovered that Barnard's Star hosts a super-Earth exoplanet with a minimum mass = 3.25 $M_{\oplus}$. Thus, Barnard Star is the nearest single star hosting a planet. Barnard b has an orbital period of Porb = 233 days and a semi-major axis of a = 0.404 au. This is nearly the same distance of Mercury from the Sun. However Barnard's Star is very faint ($L/L_{\odot}$ = 0.0033) and its planet has an instellation (relative to the Earth) of $S/S_{\oplus}$ ~ 0.020. This value corresponds to the amount solar radiation at 7au from the Sun. Thus it is cold (T_{eq} = 105 K = -168° C). At face value there appears to be little chance of liquid water (and life?) on its frigid surface. (See Fig. 1 and Table 1). But as discussed below, there may still be a chance for Barnard b to be habitable.

X-ray, UV, Optical Irradiances of Barnard b

We compute the X-ray and UV irradiances on Barnard b from its M3.5 V host star - See Table 1. X-ray and UV radiation (and stellar winds & flares) play critical roles on photoionization & photochemistry of impacted planetary atmospheres. This high energy XUV radiation and stellar plasmas can result in the erosion and possible loss of a planet's atmosphere. The atmospheric loss can be especially severe when the red dwarf is young, rotates rapidly and is extremely active with strong X-ray and UV emissions that are ~600–800× and ~12–15× stronger, respectively than at old age. Also during the star's pre-main-sequence phase (which lasts nearly 200 Myr). At <50 Myr Barnard's Star would be over 10× more luminous and the planet's irradiance would be $S/S_{\oplus}$ ~ 0.2. So that at that age the young planet would be ~80° C warmer. With greenhouse gases it could be possible that briefly Barnard b was be warm enough for liquid water.

Age of Barnard Star and its Planet

Barnard's Star is one of the founding members of the Villanova *Living with a Red Dwarf* program (Engle & Guinan 2011, *ASPCS* 451) From photometry started in 2003 we determined a rotation period of P_{rot} = 142±8 days. This value agrees very well with P_{rot} = 145±15d determined from the combined analysis of all photometry & spectroscopic measures from Toledo-Padron et al. 2018 (arXiv:1812.067120). Utilizing our *Period-Age relation* for red dwarfs (Engle & Guinan 2018 *RNAAS* 2, 34) **indicates an age ~8.5±0.9 Ga**. This gyro-chronological age agrees well with other age indicators that include large *UVW* space motions and low chromospheric Ca II *HK* and coronal X-ray emissions.

Potential Life on Barnard b: Can Life find a way?

Barnard b receives only 2% light relative to the Earth and thus is cold (T = -168° C). **However, all hope for life on Barnard b may not be lost.** As a super-earth (M > 3.25 $M_{\oplus}$), Barnard b could have a large hot iron core that could result in enhanced (and because of its larger mass) prolonged geothermal activity. If water is present, geothermal heating (volcanic plumes, vents etc.) could result in liquid water "life zones" under a possible icy surface. This much like Jupiter's icy moon Europa that is heated by tidal heating rather than from geothermal energy. More local analogs for subsurface liquid water under ice are the geothermal-heated lakes in Antarctica. Although little is definitely known about geomagnetism of super-earths like Barnard b, a large liquid iron core, that could strong generate geomagnetic fields, could offer protection from strong winds and coronal mass ejections when the star was young & magnetically active. However, if the mass of the Barnard b is much higher than about 7–10 $M_{\oplus}$, its higher gravity could result in it retaining a thick H_2-He atmosphere and thus be a dwarf gas giant (mini-Neptune). In this case all hope for life is probably lost unless by chance Barnard b hosts an icy moon (with a subsurface ocean) that could be tidally heated like Europa.

Imaging Barnard b

The angular separation of the Barnard b from its host star is ~220 mas (0.22"). This is much larger than the maximum angular separation of Proxima b from its Prox Cen of ~40 mas. Although Barnard b is very faint, it may be possible to image it with future very large telescopes. Adopting an albedo = 0.5, Rp = 1.5 $R_{\oplus}$, d = 0.404 au, we estimate that Barnard b is ~ 21.3 mag fainter than the star. Adopting I-band (806 nm) = +6.74 mag and H-band (1.65 nm) = +4.83 mag measures for Barnard's Star, the reflected light of the planet would be I(p) = +28.0 mag and H(p) = +26.1 mag at full illumination. **Thus, it may be feasible to image Barnard b with future large telescopes – e.g.- the *GMT, TMT and ELT* as well as with JWST and WFIRST.** It may even be possible to secure near-IR spectroscopy of the planet. **Noteworthy Barnard b is one of only a handful of Earth-size that can be directly imaged.** Such observations will illuminate the nature of the planet's atmosphere /surface and potential habitability. Also it may be possible to determine the mass of the planet from continued high precision astrometry with *Gaia* (see Ribas et al. 2018). However, the large proper motion of Barnard Star will make this a challenge.

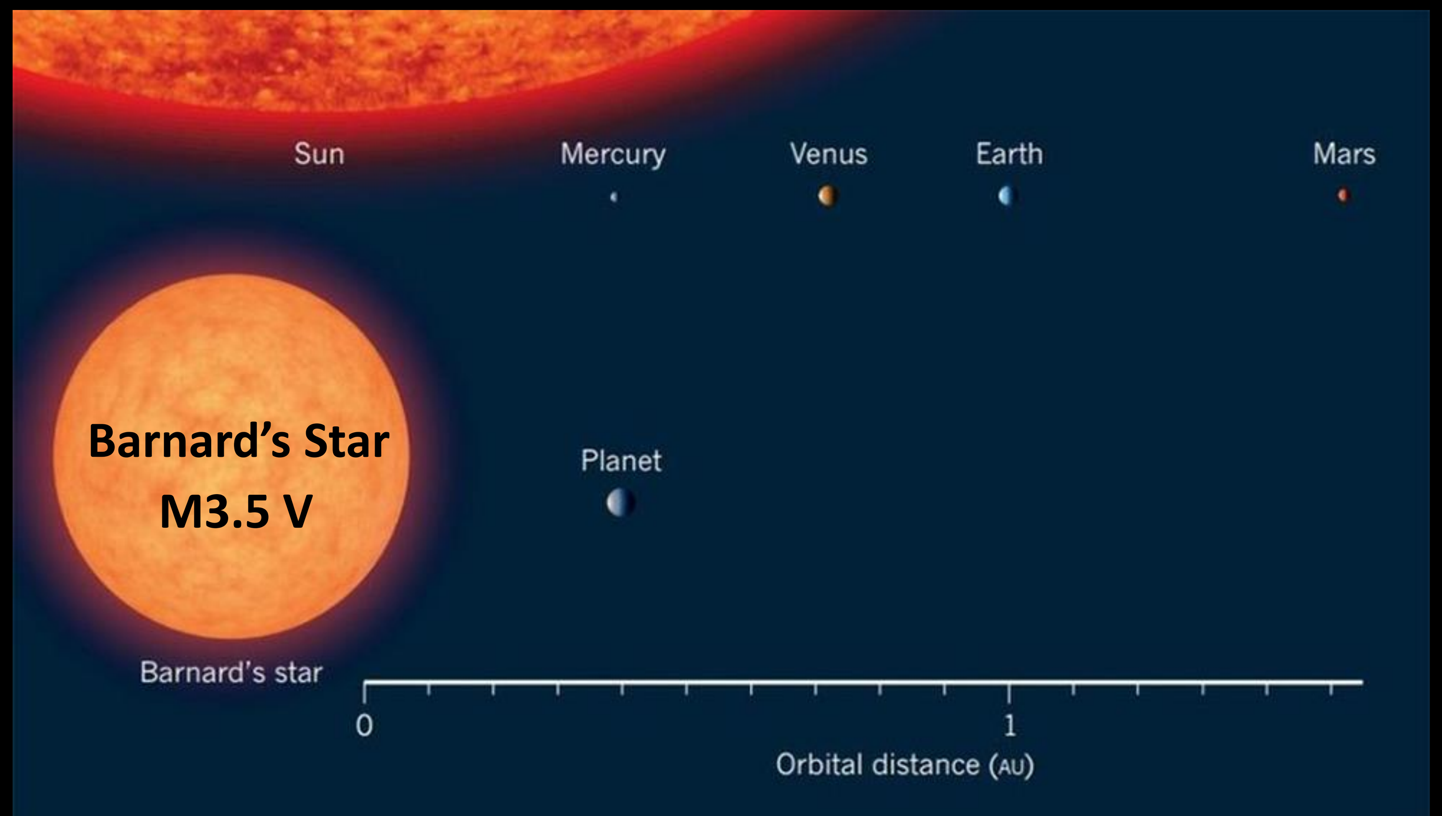

Fig.1. Model of the Barnard Star planet system (from Ribas et al. 2018) compared to the inner Solar System. Barnard b orbits at 0.404 AU from its M3.5 V host star and has an equilibrium temperature of T = -168 C., P_{orb} = 233-d and Mp x sin i = 3.25 $M_{\oplus}$.

TABLE 1

Comparison of Barnard b with Earth and Proxima b

Property	Earth-Sun [1.0 AU]	Proxima b [0.049 AU]	Barnard b [0.404 AU]	Barnard b (when young)
Age (Gyr)	4.57	5.1+/0.6	8.5+/-1.0	50 Myr
Mass (ME)	1.00	>1.27	>3.25	>3.25
Radius (RE)	1.00	1.1	~1.5	~1.5
S/SE	1.00	0.65	0.022	0.2
Teq (K)	255 [288]	227 [*277]	105 [*155]	186 [*236]
<fx>*	0.25 c.g.s.	163 [652 fx-E]	0.133 [0.53 fx-E]	90 [370 fx-E]
<f Ly-alf>* (FUV)	7.38	130 [17.6 fuv-E]	2.59 [0.35 fuv-E]	34 4.6

S/SE = instellation relative to Earth-Sun at 1.0 AU; <f> mean irradiances [flux units: c.g.s = ergs/s/cm^2]
X-ray and Ly-alpha Irradiances on Earth: 0.25 and 7.38 ergs/s/cm^2; Use <Lx> sun = 7.0 x 10^{+26} erg/s Ayres 2018
*T [GH enhancement of 50K]

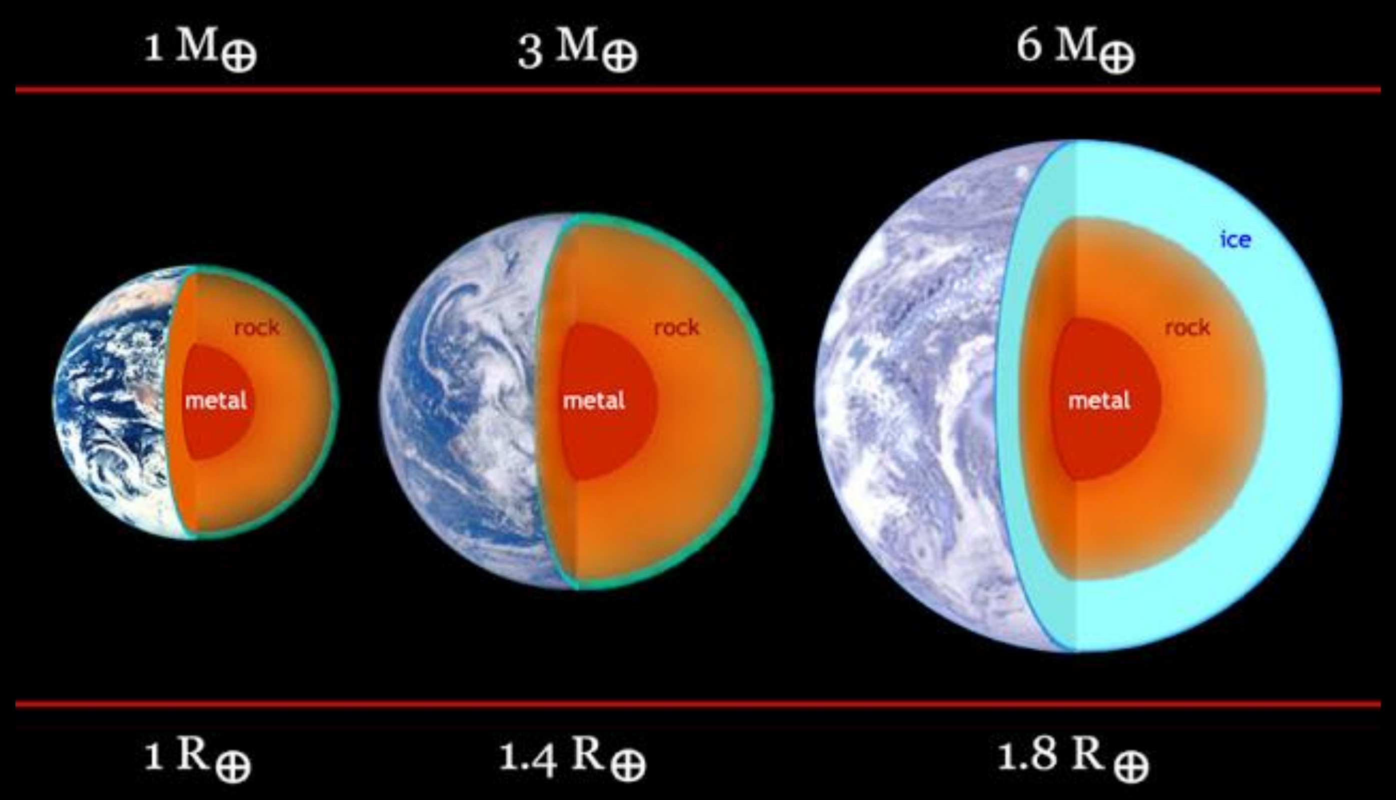

Fig. 2. Some models of (rocky) Super-Earth planets located near or beyond the cold edge of the star's habitable zone are shown. Barnard b has M > 3.25 $M_{\oplus}$.

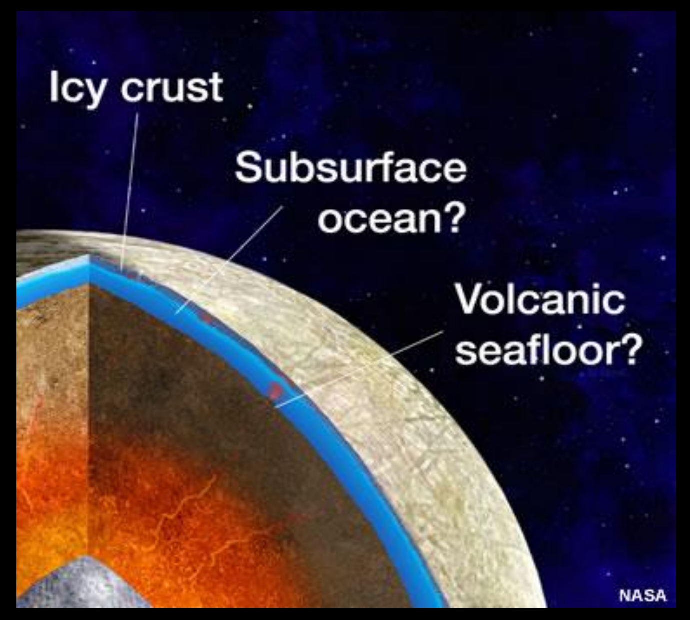

Fig. 3 Possible model of Barnard b based on geothermal heating. If water is present, geothermal heating could create a subsurface ocean where primitive life could exist. The model would be a scaled-up Europa.

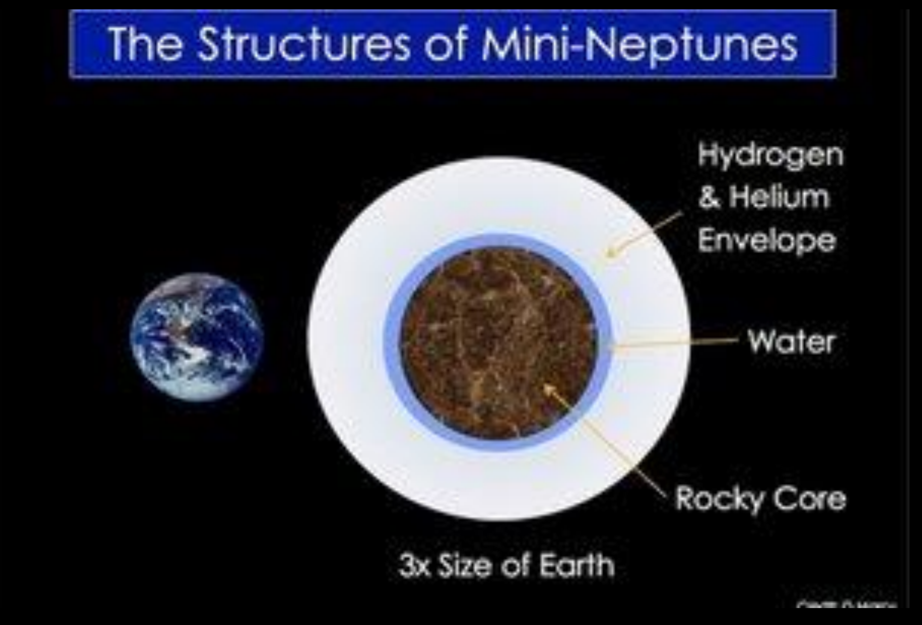

Fig.4 In another scenario if the mass of the exoplanet is > 7 $M_{\oplus}$, then the stronger gravity could cause the retention of its primordial H2/He atmosphere. These planets are known as Mini-Neptunes / Dwarf Gas Giants.

Conclusions

1. The age of the star/planet of 8.6±1.2 Ga was determined from Rotation-Age-Activity relations for red dwarfs from (Engle & Guinan et al. 2018), using input parameters from Toledo-Padron et al. (2018).

2. Barnard b receives only 2% of radiation as the Earth and is thus cold. But as super-earth (M >3.3 $M_{\oplus}$), it could possess a large, hot liquid-iron core & have geothermal energy. Geothermal energy could heat the exterior of the planet via plumes and vents. If water is present, the planet would be ice-covered, but due to geothermal heating could have subsurface water that provides niches for life.

3. Although faint, Barnard b proximity & relatively large ~220 mas separation from its host star, makes it an ideal target to try to image. It may be feasible to image Barnard b in Near-IR with JWST.

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Fig. 5. Barnard Star and its planet Barnard b are depicted in this best case scenario for potential life - that geothermal heating melts ice, producing regions of liquid water near the surface. We note that at present there are no data to support this hypothesis.