PHYS2082 Mystery Planet 2

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1 Introduction

Since the advent of the first report, a wealth of new information was collected both about the “dot” and of the surrounding neighbourhood of the Twinky System. One of the most notable pieces of this new information is that the “dot” mentioned in the previous report actually consists of a binary planetary system, composed of the aptly named 'Component A' and 'Component B'. To assess the likelihood of life originating from this system, the blackbody spectrum of each component must be modelled, and the conditions on each component must be determined. Not only is there some element of risk by approaching the planetary system, but there exists a non-zero danger of supernovae in this extremely dense region of the galaxy. As such, a classification of the nearby stars must also be made in order to quantify this risk and is made possible by the creation of a HR diagram.

2 The Planetary System

In order to eventually plot the blackbody spectrum of components A and B, first the surface temperature of each planet was found. To do this, the central star's light was deemed negligible on the photometry data for $\lambda \geq 10000$nm (a suitable approximation considering that the stellar flux at that wavelength and distance was orders of magnitude less than that observed for components A and B in the data). Considering that each point corresponds to a value of the *same* blackbody curve at a different wavelength, the ratio of the 10000nm and 20000nm photometry data was taken:

$$\frac{4\pi^2 R^2 B_1}{4\pi^2 R^2 B_2} = \frac{L_1}{L_2} \implies \frac{\lambda_2^5 \cdot \left(e^{\frac{hc}{\lambda_2 kT}} - 1\right)}{\lambda_1^5 \cdot \left(e^{\frac{hc}{\lambda_1 kT}} - 1\right)} = \frac{L_1}{L_2} \implies e^{\frac{hc}{\lambda_2 kT}} - 1 - \frac{L_1}{L_2}\frac{\lambda_1^5}{\lambda_2^5}\left(e^{\frac{hc}{\lambda_1 kT}} - 1\right) = 0$$

This is clearly a difficult equation to solve for T, and so the equation was plotted to find a value of T such that the rightmost expression was satisfied (i.e. the function was plotted with T as the independent variable, and the single root of the function corresponded to the desired temperature). Using the luminosity values of each component for $\lambda_1 = 10000$nm and $\lambda_2 = 20000$nm, and substituting all values into the expression yielded a root at $T_A \approx 108.3$K for component A, and $T_B \simeq 140.5$K for component B. While this is one more significant figure than the photometry data gives, the planck function plotted later on was extremely temperature dependent, and the observed values were only approximated by the model with the 4 significant figures quoted in these temperature values.
To model the blackbody spectrum of each component in terms of its specific luminosity, it was hypothesized that the spectrum would fit the sum of the planet's own blackbody spectrum and a fraction of the stellar spectrum reflected off the planet, scaled down by some scaling factor s_i:

$$L_i(\lambda) = s_i \left(A_i L_s(\lambda) + L_p(\lambda)\right)$$

where $L_i(\lambda)$ is the observed luminosity, L_p the planet luminosity, A the albedo, R the planet radius, $L_s(\lambda)$ the stellar luminosity, and s_i a scaling factor dependent on telescope, material and orbital properties. Expanding

L_s in terms of the flux at the distance of the planet's orbit, and accounting for the planets' cross-section absorption of stellar radiation, this becomes:

$$L_i(\lambda) = s\left(A_i \frac{4\pi^2 R_s^2 \cdot \pi R_i^2 B_s(\lambda)}{4\pi d^2} + 4\pi^2 R_i^2 B(\lambda)\right)$$

where R_s is the star radius, B_s is the star's planck curve, and d is the orbital distance of the planet from the star. Once again expanding the equation in terms of the spectrum and temperature gives:

$$L_i(\lambda) = \frac{s \cdot 2\pi_i^2 hc^2}{\lambda^5}\left(A_i \frac{R_s^2 \cdot R_i^2}{d^2\left(e^{\frac{hc}{17000k\lambda}} - 1\right)} + \frac{4R_i^2}{\left(e^{\frac{hc}{kT_i\lambda}} - 1\right)}\right) \tag{1}$$

where two of these values were calculated in the last task: $R_s = 2.95 \times 10^9$m and $d = 2.54 \times 10^{13}$m. Combining the model with all of these values gave the blackbody spectrum below:

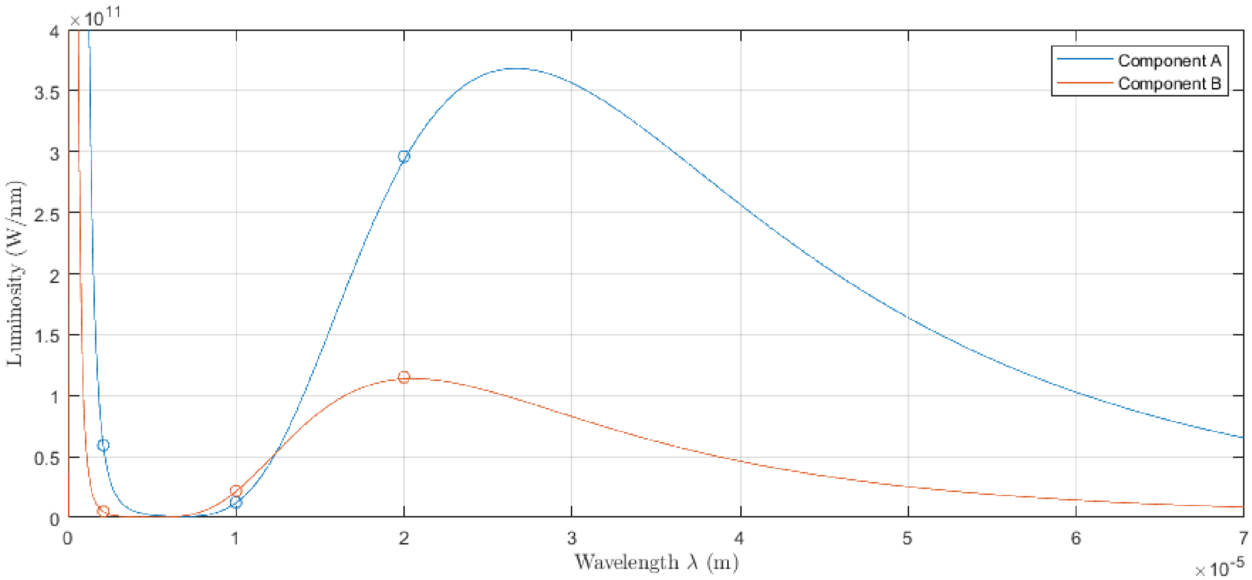

Figure 1: Comprehensive Blackbody Spectrum of Planetary System Components

As Figure 1 shows, Component A is consistently more luminous than Component B at all wavelengths except a small region around 10000nm. This is likely due to Component B being about 30K hotter than Component A, and so its thermal signature in the near infrared would be more luminous. Worth noting is the sharp spike towards the lower wavelengths, which is the reflected light from each planet due to Twinky.

3 The Signal

To help assess whether or not to approach the planetary system, the radio signal radiating from it must be investigated.

Firstly, the radio data was analysed. The graphs supplied in the handout were determined to have large interval ticks of 10000 seconds, and small interval ticks of 1250 seconds. With that known, the duration between peaks (and the subsequent drop) were determined to be 71250 seconds – and so the period of the two components orbit was $P = 71250$s. Of note was the pure sinusoidal shape of the radio frequency curve, which necessitates that the two components of the system are in a circular orbit with respect to each other.

Since the separation between the two objects was well defined as $a_A + a_B = 81000$km, the combined mass was found as

$$P^2 = \frac{4\pi^2}{G(m_A+m_B)}(a_A+a_B)^3 \Longrightarrow m_A + m_B = \frac{4\pi^2}{GP^2}(a_A+a_B)^3 \simeq 6.20 \times 10^{25}\text{kg} \tag{2}$$

This value will become particularly important soon, but another important aspect of the radio curve must be discussed: the periodic loss of signal. Since the signal is lost between peak and trough, the source is obscured by some object for exactly half of the orbital period. This, together with the eclipse that occurs about the equilibrium position of frequency (1420MHz), means that at least one of the two components are tidally locked to the other; as the radio source moves away from the observer (but is still in view), the frequency is redshifted below the equilibrium frequency of 1420MHz. As the radio source is just about to point towards the observer (at 1420MHz with no red/blueshift), it is blocked by the other component in the system and the signal is lost for a short time. Once it reappears, it is moving towards the observer in its orbit and it appears to be blueshifted above the equilibrium frequency until it reaches halfway through its oscillation at which point the source is obscured by its own planet as it faces away from the observer and to the other component in the system.
Using this amount of blue and redshift, more crucial data about the system can be calculated. Using the radio frequency graph, the source was determined to have a frequency shift of 0.022MHz (since the y-axis ticks were 0.002MHz in height) and so the radial velocity of the source can be estimated using the well-defined relation:

$$\frac{\Delta\nu}{\nu} = \frac{v}{c} \Longrightarrow v = \frac{\Delta\nu}{\nu}c = \frac{0.022\text{MHz}}{1420\text{MHz}} \cdot c \simeq 4.6 \times 10^3\text{m/s} \tag{3}$$

Note that this velocity corresponds to the component that has the signal source on its surface. Since the radio frequency graph has an eclipse of approximately 3750 seconds (3 duration small ticks), this would correspond to the radio source travelling approximately 17250km during the duration of eclipse. Assume for the moment that the radio source is of small width (in comparison to the diameter of component B) and on the surface of Component B (centered at the point on the sphere closest to Component A). Then the radio source moves in one direction 17250km over the course of the eclipse. The distance travelled by Component A (in the other direction) over the same period is found first by finding the orbital radius of components B and A:

$$\begin{aligned} P = \frac{2\pi a}{v} &\Longrightarrow a_B = \frac{Pv_B}{2\pi} = \frac{71250 \cdot 4.6 \times 10^3}{2\pi} \simeq 5.2 \times 10^7\text{m} \\ a_A + a_B = 81000\text{km} &\Longrightarrow a_A = 8.1 \times 10^7 - a_B \simeq 2.9 \times 10^7\text{m} \\ &\Longrightarrow v_A = \frac{2\pi a_A}{P} = \frac{2\pi \cdot 2.9 \times 10^7}{71250} \simeq 2.6 \times 10^3\text{m/s} \end{aligned}$$

These calculations correspond to a *relative* distance travelled of about 27000km over the period of the eclipse (which is very close to two Component A radii, especially when accounting for its thick atmosphere [see the next page] which is likely at least partially transparent to radio at higher altitudes). Now, comparing this to if the radio source were on Component A's surface, the exact same relative change in distance would have occurred (according to the symmetry of the calculations above). However, the eclipsing component in this case would be Component B which is far smaller in radius than Component A. The eclipse in this case would last for at most 2 ticks width on the radio frequency graph (corresponding to 18000km relative distance, just over 3 Component B radii), and so the source *must* be on Component B's surface due to the long duration of the eclipse. With these parameters now verified, the planetary system resembles that shown in Figure 2 (orbits displayed to scale with one another, as are the planets, but the orbits not scale with respect to the planets):

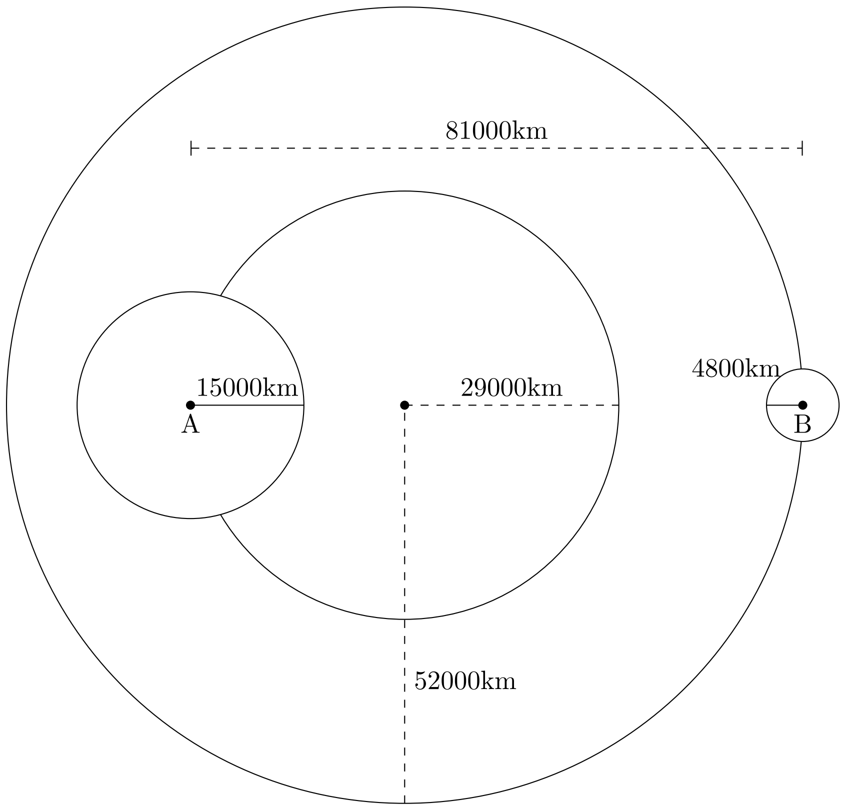

Figure 2: System Layout of Components A and B

To help estimate the source of the signal, more details about each component must be inferred, including the masses of each component and their corresponding densities. Using the mass/semi-major axis relation for binary companions, the ratio of masses for Components A and B is:

$$\frac{m_A}{m_B} = \frac{a_A}{a_B} = \frac{5.2}{2.9} \simeq 1.8$$
$$\implies m_A = 1.8 m_B$$

Then, the mass of each component can be estimated by substituting this into equation (2):

$$\begin{aligned} m_A + m_B &= 1.8 m_B + m_B \\ &= 6.20 \times 10^{25}\text{kg} \\ \Rightarrow m_B &\simeq 2.2 \times 10^{25}\text{kg} \\ \Rightarrow m_A &= 6.20 \times 10^{25} - m_B \\ &\simeq 4.0 \times 10^{25}\text{kg} \end{aligned}$$

And now since the masses and radii of each component are known, their average densities may be calculated:

$$\rho_A = \frac{m_A}{V_A} = \frac{4.0 \times 10^{25}\text{kg}}{\frac{4}{3}\pi(1.5 \times 10^7\text{m})^3} \simeq 2.8 \times 10^3\text{kg/m}^3$$
$$\rho_B = \frac{m_B}{V_B} = \frac{2.2 \times 10^{25}\text{kg}}{\frac{4}{3}\pi(4.8 \times 10^6\text{m})^3} \approx 47 \times 10^3\text{kg/m}^3$$

The implications of the above density calculations are profound. Firstly, component A has a density between what one would expect of a gas giant and a rocky, terrestrial planet which is expected considering its radius straddles the line between the two. This density implies that there would be a very thick atmosphere that extends to a significant altitude above a potential surface on the planet – a result which is required for the previous assumption that the radio source lies on the surface of Component B.
The second conclusion to be made from this is that the density of Component B is not like any known material (its density is more than *twice* that of Osmium, the densest known material). In fact, the calculated density is comparable to the estimated density of the core of a low-mass star. The surface gravity on Component B would be approximately 6.5g – much too strong to sustain a human presence.

The physics that could maintain such a low-mass object at such a high density is unclear, but could help explain the observations of the radio signal. From looking at the radio flux graph, it appears to peak at an observed flux of $F = 9.0 \times 10^{-16}$ W/m^2, which, observed at a distance of $d = 323$AU (the minimum distance reached by the observation drone before malfunction) would correspond to a source power of

$$F = \frac{L}{4\pi d^2} \implies L = 4\pi F d^2 \simeq 2.6 \times 10^{13} \text{ W}$$

Clearly this power is far greater than any point on Component B's blackbody spectrum (ignoring the reflected light), and so it is not the result of the temperature profile of the 'planet'. Entering into the realm of speculation, there are few explanations that could describe this.
The most plausible explanation would be an intense magnetosphere interaction between the two planets and Twinky. This idea relies on Component B having a magnetic axis misaligned from its rotation axis by 90 degrees such that one magnetic pole is always pointing towards Component A. This is in part supported by planetary radio emissions having been found in our own Solar System, with the interaction of Jupiter and Io with the Sun's solar wind producing MHz frequency radio waves. This magnetic field could also help explain the density of Component B, provided that the magnetic field helps keep the component material compact. As to how such an object formed, it is unclear. Perhaps a massive, highly magnetized object had its outer layers stripped away from gravitational interactions with Twinky and Component A. Perhaps the repeated, tidal heating caused by close-flybys with Twinky (an account of its highly elliptic orbit calculated in the first report) sustain an active, molten core in Component B that keeps the object compact.

Whatever the mechanism of formation of Component B, it is *unlikely* that an organic alien lifeform is present due to the extremely low temperature of about 140K. If some alien civilization were to inhabit this 'planet', it could not be life as we know it but perhaps some robotic lifeform that relies on low temperatures and a strong magnetic field.
It does beg the question that if some civilization were to put a radio emitter here in the form of the entire Component B, *why?* The Twinky system does not appear to be particularly interesting as far as stellar systems go, and if a strong magnetic field is what this civilization needs then a neutron star system would be far more attractive. On the note of the power of the radio source, $\sim 10^{13}$W is orders of magnitudes higher than the output of even the most powerful power plants on Earth, and so it would make little sense to be radiating that energy away into space purposefully, lest such a civilization would want to be found. It is worth noting that the frequency of the signal, 1420MHz, is a well known and abundant radio frequency in the Milky Way. It typically originates (naturally) from an electron spin flip in a neutral hydrogen atom. That is not to say that this signal is *definitely* natural in origin, but rather that it *can* be produced by natural processes – perhaps from interactions of stellar wind with a hydrogen atmosphere on component B.

4 Danger in the Neighbourhood

Since the Twinky system is in such a dense region of the Milky Way, the density of dangerous stars is correspondingly higher. To help determine the risk of supernovae, the local region had to be classified.

Firstly, Cluster A was analysed to act as a sort of 'calibration' cluster for the other two in order to assess the risk they pose. Using the defined flux-luminosity relationship of known distance, the V-band luminosities for each of the variable stars in Cluster A were calculated, with the angular distance of 0.017 arc seconds. Figure 3 [next page] shows the relationship between the V band luminosity and the periodicity of the stellar fluctuations for the Cluster A stars. Clearly, these can be divided into two distinct (approximately) linear trend lines, which apply to variable stars of relatively short or long periodicity.
Upon observation of the Cluster B and C variable data, the variable stars in Cluster B have similar periodicity to the less luminous Cluster A variables, while the variables in Cluster C resemble those of the more luminous Cluster A variables. Using a linear trendline, and the fact that the luminosity axis is a log scale gives:

$$L_{B,V} = 10^{2.086P+20.83}\ \mathrm{W} \qquad L_{C,V} = 10^{0.684P+25.83}\ \mathrm{W}$$

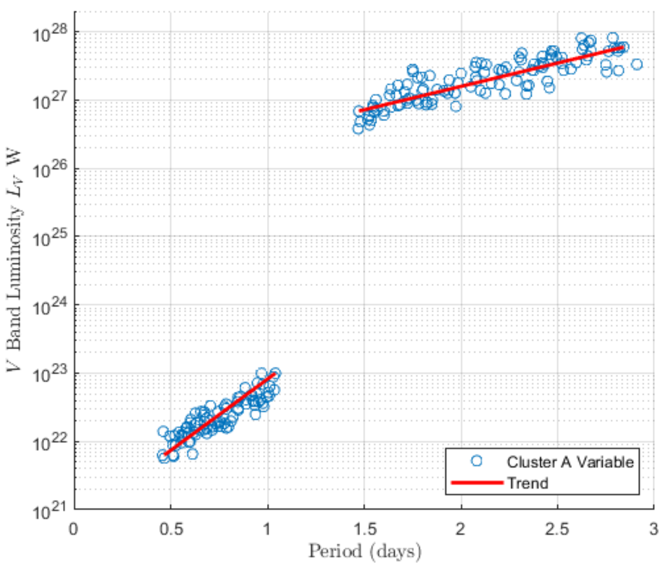

Figure 3: Cluster A Variable Star Luminosity Vs Period

From this, the V-band luminosity of each of the variable stars in each cluster was estimated, and the distance to each could be inferred using this luminosity and the V-band flux. The approximate distance to the center of the cluster was estimated by taking the average of all of the calculated distances to the variable stars. This approximation was made under the assumption that the clusters were approximately spherically symmetric with a larger star density towards the center of the cluster, and so a random sample of stars from the cluster (in this case, the variable stars) would be randomly distributed about the center of the cluster. By taking the average distance of each star in the sample, the approximate average distance of the telescope from the center of each cluster was found to be $d_B \simeq 240.1\text{pc}$ for Cluster B, and $d_C \simeq 1505\text{pc}$ for Cluster C. The relative error in these measurements for Cluster B were larger than that of Cluster C, considering that there was a maximum spread of $\pm 20\%$ from the mean for Cluster B and $\pm 15\%$ for Cluster C.

Now that the distance to each cluster center was estimated, it's clear that some calculation of absolute magnitude was to be made in order to classify the stars and create a HR diagram. Using the well-defined relationship between flux and apparent magnitude, the apparent magnitude of each star could be calculated (as could the colour index):

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{F_1}{F_2}\right) \Rightarrow m_V = m_{V,\odot} - 2.5\log_{10}\left(\frac{F_V}{F_{V,\odot}}\right) \tag{4}$$

$$B - V = m_B - m_V = -2.5\log_{10}\left(\frac{F_B}{F_V}\right)$$

To calculate the *absolute* magnitude of each star, the well-defined relationship between apparent and absolute magnitude over distance was used:

$$100^{(m-M)/5} = \left(\frac{d}{10\text{pc}}\right)^2 \Rightarrow M_V = m_V - 2.5\log_{10}\left(\frac{d}{10}\right)^2 \tag{5}$$

where the distance is measured in parsecs, and was approximated as the average distance to the star cluster. As per Bruce Gary (2014), the average solar flux over the V photometric band is approximately $F_{V,\odot} = 185\text{W/m}^2$, and the apparent magnitude of the Sun (from Earth) is $m_{V,\odot} = -26.72$. Combining equations 4 and 5, as well as substituting in known values gives

$$M_V = m_{V,\odot} - 2.5\log_{10}\left(\frac{F_V}{F_{V,\odot}} \cdot \left(\frac{d}{10}\right)^2\right) = -26.72 - 2.5\log_{10}\left(\frac{F_V}{185} \cdot \left(\frac{d}{10}\right)^2\right) \tag{6}$$

Using the approximate average distance to each cluster, as well as each star's individual V-band flux allowed for the creation of the HR diagram shown in Figure 4:

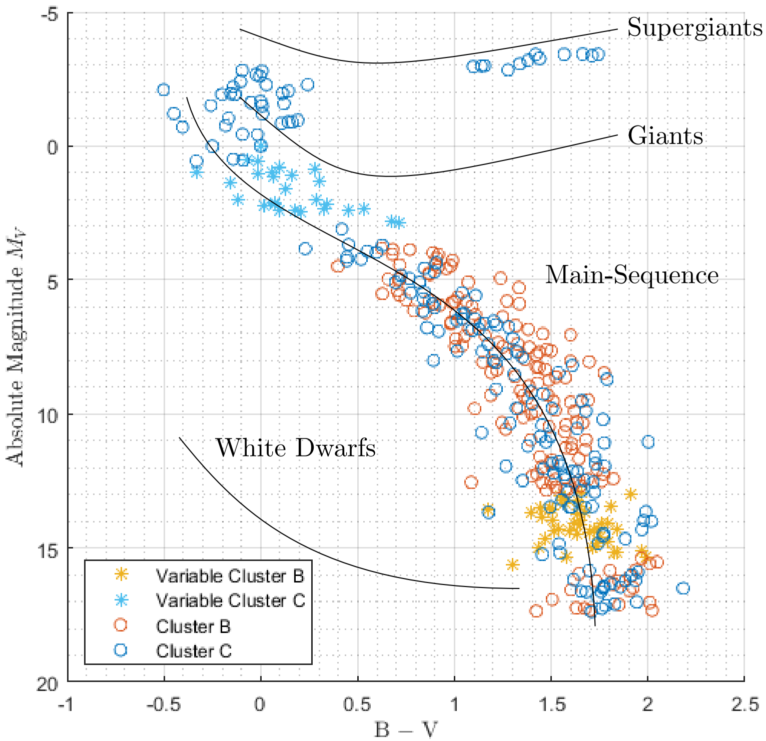

Figure 4: Stacked HR Diagram of Cluster B and C Stellar Data

The data shown in Figure 4 is approximate only (on account of the assumptions alluded to previously) and is less accurate for stars closer to or further from the telescope relative to the center of the cluster.
The stellar classification lines, plotted in black, are qualitative only and show the *approximate* locations of where to expect such stars. Each data point, however, is quantitative and calculated from the stellar photometry data according to equation 6.

From this HR diagram, there appear to be no white dwarfs present within either cluster which suggests that both clusters are relatively young in that no intermediate-mass stars have 'died'.

By inspection, the "turn-off" points of each cluster appear to be at about $-2M_V$ for Cluster C, and 4 M_V for Cluster B. On cross-reference with Figure 14.8 in Carrol and Ostlie, this puts the current turn-off mass at *about* $5M_\odot$ and $1.5M_\odot$ for clusters C and B respectively. By cross-reference with Figure 13.19 in the same text, a *rough* age of 30 million years and 7 billion years was estimated for Clusters C and B respectively. This means that there is still some risk of supernova in Cluster C soon (in astronomical terms), but no star in Cluster B is likely to undergo core collapse ever again.
On observation of Figure 4, the Cluster B variable stars appear to be cool, dim red dwarfs, while the cluster C variables appear to mostly be slowly-pulsating-B stars (SPB stars) which are characterised by periods between 1 and 5 days and luminosity variations driven by g–mode pulsations.

From the distribution of each cluster's stars on the HR diagram, cluster B is clearly populated primarily by low mass stars which are currently of no risk to the Twinky system. This comes as a relief considering that cluster B is much closer to the system at an average distance of only 240.1pc. The case could be made that some of the higher mass stars in cluster B are just beginning to transition off of the main-sequence due to their distance away from the main-sequence trendline, but are still a considerable time away from a supernova in any case.

Cluster C seems to be composed of a mix of stellar masses which results in a broad distribution across the HR diagram. The presence of bright–giant/supergiant stars carries with it some risk to the Twinky system in terms of possible supernova explosions. Richmond (2005) suggests that Type Ia supernovae inflict a lethal dose of ionizing radiation on a human according to the rule heavily dependent on the distance away the explosion occurs. Since core-collapse supernovae are typically 10 times less luminous (and so it would take 10 times as long to inflict a lethal dose), the relationship between the time to lethal dose (seconds since first observation) and distance (pc) from a supernova is:

$$t_{\mathrm{LD(Ia)}} = 0.3d^2 \qquad \Longrightarrow \qquad t_{\mathrm{LD(cc)}} = 3d^2 \tag{7}$$

(which was derived from the tabulated data in the mystery planet handout). Using the core-collapse variant of equation 7 and the distance to Cluster C $d_C \simeq 1505$pc, the time to lethal dose from a core-collapse supernova in Cluster C would be $t_{\mathrm{LD,\ C}} \simeq 78.65$ days. To avoid exposing the crew to ionizing radiation, the spacecraft could be situated behind some large object in the Twinky system to effectively shield it from radiation. The obvious candidates for which include Twinky, and Components A and B which each carry with them subsequent risks. Firstly, the probe malfunction at a distance of 323AU from the planetary system implies that the closer the spacecraft is to the system, the more likely it is to either malfunction or risk interfering with any lifeforms. Alternatively, 'hiding' behind Twinky would mean that Twinky would need to subtend a large enough angular diameter in the plane of the sky to block all the incoming supernova radiation. Being so close to the star would mean exposing the spacecraft to the ionizing radiation of the star which peaks in the UV spectrum (as per the first report, the peak in the spectrum is at approx 170nm).

5 Conclusions

Through analysis of the shape of the incident radio signal, as well as a picture of the system, key characteristics about the planetary system orbiting Twinky were determined. The radio signal was sourced to the surface of the system Component B, which itself makes up just over one third of the mass of the system and interestingly has a density of $\rho_B \simeq 47\times10^3\mathrm{kg/m^3}$ – higher than any known substance. This was hypothesized to be either the cause or the byproduct of an intense magnetic field that, upon interaction with a magnetic field stemming from Component A, could have been producing the observed radio signals at the observed power of 2.6×10^{13}W. Due to this intense magnetic field, it is recommended that the spacecraft does not approach the planetary system any closer than necessary. Alternatively if an alien civilization were to be responsible for these signals, and consequently the demise of the probe sent to investigate the system, the recommendation remains the same.
On the note of the system's characteristics, the two components were determined to follow circular orbits about a common barycenter with Component B tracing a larger path on account of its lower mass compared to Component A. Component A was found to be somewhere between the density of gaseous and terrestrial planets, and so it was inferred that a thick and high atmosphere was present. A blackbody model was created for the two components which perfectly described the observed data. The corresponding temperatures that the model required were $T_A \simeq 108.3$K for Component A, and $T_B \simeq 140.5$K for Component B. This low temperature, together with the likely strong magnetic field and 6.5g surface gravity, makes Component B inhospitable to human life and the sensitive technology that comes with a human presence.

In conjunction with the aforementioned risk due to the planetary system, the region of the galaxy that the Twinky system is located in provides risk in itself. By studying two nearby star clusters, B and C (of distance $\simeq 240.1$pc and $\simeq 1505$pc respectively), the danger of supernovae in the region was assessed. First by plotting a HR diagram using observed stellar flux data, it was found that there are several near-supergiant stars in Cluster C which pose some risk in the next thousands of years. Using data from Richmond (2005), a model for the time-to-lethal-dose of supernova ionizing radiation was determined and by using this the time to lethal dose from a supernova in Cluster C was found to be about 78 days. In this extreme event, it was recommended that the spacecraft situate itself with Twinky *between* the spacecraft and the radiation source to limit the exposure to ionizing radiation. While 'hiding' behind one component of the planetary system could also work, it was recommended that the system should be avoided.

All in all, the Twinky system and this particular region of the galaxy was deemed generally hostile towards any presence of life; the main takeaway of this report is to leave the area at the earliest convenience.

References

[1] Gary, B, 2014. "*Deriving a Magnitude System*" Available at: http://brucegary.net/Dawn/allskydetails.html [Accessed 23/10/2021]