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Detached Compact Object Binaries in Gaia Data

Alvaro Herrera[1], Ryosuke Hirai[2], and Ilya Mandel[2]

[1] University of Florida, Gainesville, FL 32611, USA
[2] School of Physics and Astronomy, Monash University, Clayton, Victoria 3800, Australia

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ABSTRACT

Compact objects, the last stage in stars' evolution, are known to be difficult to detect and often require special techniques to identify. Gaia, a telescope of the European Space Agency designed for astrometry, is one way to identify compact objects in astrometric binaries. The recent Gaia Data Release 3 records over 1 billion systems, some of which are astrometric binaries and therefore may contain compact objects. The focus of this project is to identify systems within Gaia data that are astrometric binaries containing compact objects and attempt to characterize these systems to learn something about binary evolution with COMPAS—a binary population synthesis code.

1. Introduction

A compact object is the last stage of a star's evolution. But unlike other periods of a star's life, no nuclear fusion happens during the compact object phase. Since nuclear fusion produces heat and gives a stellar object its temperature, a compact object—excluding black holes—gradually gets cooler, meaning that it becomes less visible—electromagnetically—over time. Hence, trying to detect these objects is generally difficult. One way to identify compact objects is through astrometric binaries; an astrometric binary is a system of two stars where one component is visible and bright, whereas the other is comparatively dim or plain invisible. So, if a bright star is seen to be periodically moving in space, with no visible companion, one has identified an astrometric binary and can in principle calculate what the companion's mass must be to keep the visible companion in orbit and can infer what kind of object it is.

Gaia Data Release 3 provides us with information on these sorts of binaries with may contain compact objects. Determining whether the invisible companions in these binaries are compact objects is not clear-cut and requires statistical analyses: if we can determine the stellar type of the luminous component, what are the possible kinds of companions it can have, and what is the most likely. Using COMPAS, a binary population synthesis code, we can make inferences on what kinds of stellar objects the invisible companions could be, and we can also learn about how such binaries formed.

To carry out this process, I developed a set of tools that can calculate the color and magnitude of a star—or binary system—given a luminosity, temperature, spectral distribution, and pass band transmissivities for the specific telescope used. I also wrote a piece of code that can calculate the mass and age of a main sequence star, given a color and magnitude since there was no functionality already built into COMPAS. With these tools it then becomes possible to obtain the color and magnitude of COMPAS systems and compare them with the color and magnitude with observable systems in Gaia. I am then able to get the mass and age of stars from systems which have appear to have a main-sequence star. Obtaining the component types in Gaia binary systems and their mass and age from various COMPAS runs then allows for statistics regarding what the component types can be.

Unfortunately, I was not able to reach the part of doing various COMPAS runs and obtaining statistics for what the components within Gaia systems could be; by the time I was ready to do so I had one week left in the program. So, I do not have results on that part of the project, meaning I will have to focus on the making of my tools and the reasons for doing so in this paper. I will also show examples of my tools working as intended.

2. Background

The binaries we are interested in have at least one luminous component, meaning that it emits a considerable amount of electromagnetic radiation; therefore, one must model the spectral distribution—the intensity per unit of wavelength—of a star. This electromagnetic radiation is a consequence of nuclear fusion within the star's core, which releases some amount of energy as photons. Those photons then journey through the various layers of a star, constantly being absorbed and reemitted as photons of different energies than when they started. After escaping the star's photosphere, the photons then begin their long journey in outer space. The number of photons of a particular wavelength emitted per unit area of the star's surface is then the spectral distribution. Typically, the spectral distribution one uses for a star is the Planck distribution, since stars are typically good black bodies. However, we will later see that there is deviation from the blackbody model for stars.

The device used to capture a star's electromagnetic radiation is called a photometer, and what it measures is intensity, the power radiated onto the surface area of the device, which is also called flux by astronomers. Since photometers can be made sensitive to ranges of wavelengths, you can filter out certain wavelengths from being measured by your photometer; this filter is called a passband. The Gaia observatory has three different passbands: the G band—sensitive to wavelengths between 320 and 1100 nanometers—the BP band—sensitive to wavelengths between 320 and 750 nanometers—and the RP band—sensitive to wavelengths between 710 and 1100 nanometers. So, when you use a photometer with a passband you are sampling the spectrum of the star weighted by the system response function of the passband as a function of wavelength.

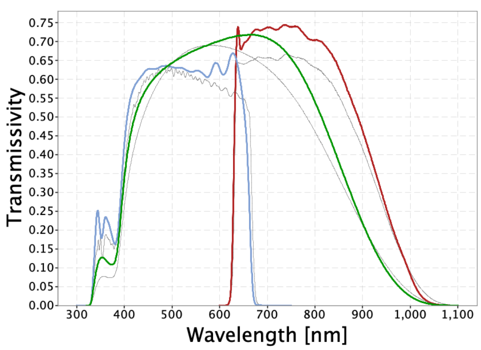

Fig. 1. Gaia Data Release 3 Passbands

The photometer measures the intensity—flux—of a star in a passband, but instead astronomers like to use magnitude as a measure of the brightness of a star. Magnitude is a dimensionless, logarithmic quantity; one magnitude is defined as a ratio of brightness of 2.512 times, meaning that a magnitude 2 star is 2.512 times as bright as one of magnitude 1. Hence, a difference in n magnitudes corresponds to a brightness ratio of 2.512^n to 1. Furthermore, there are two different kinds of magnitude: absolute magnitude and apparent magnitude. Absolute magnitude describes the intrinsic brightness of a star. Apparent magnitude is the brightness of a star as it appears in the night sky from Earth, so it depends on the star's intrinsic luminosity, its distance, and the absorption/scattering of its light by dust and gas (extinction) between the star and Earth. Since Gaia is orbiting Earth, it is—to a good approximation—looking from Earth; therefore, it is measuring apparent magnitude. From apparent magnitude, one can obtain a star's absolute magnitude since the two are related by $m - M = 2.5 \log_{10}(d/10)^2$. If there is extinction due to the absorption of light by dust particles between the star and observer, one must add an extinction term to this relation.

In practice, observatories, such as Gaia, have multiple passbands, so magnitudes can be calculated for each one. Subtracting two magnitudes from different passbands gives a quantity called color. If you, for example, subtract the magnitude obtained through the red Gaia filter from the magnitude obtained through the blue Gaia filter, and end up with a positive number, then the object in question is blue; if you end up with a negative number, then the object is red. Therefore, this subtraction of magnitudes through different passbands tells you something about the color of a star, hence the name of the quantity. If you know both the color and absolute magnitude of the star in a passband, you can place the star in a color-magnitude diagram (CMD). Color-magnitude diagrams were created and developed as a tool to classify stars in the 20th century, representing a major step towards an understanding of stellar evolution; nowadays, plotting stars on a color-magnitude diagram gives insight into stars' types and where they lie on their evolutionary tracks, which is useful for the purposes of our project.

3. Building Tools

The Gaia Data Release 3 on June 13th of 2022 filled the Gaia archive with around 1.46 billion sources with full astrometric solutions. From these sources, catalogs were made that categorized what sort of sources these seemed to be. The relevant catalogs for our project are those with possible compact object companions. The first such catalog available was Ellipsoidal Variables with Possible Black-Hole or Neutron Star secondaries by R. Gomel et.al. This catalog had 6306 possible compact object secondary candidates, so it was something to look at.

The way we were going to work with these systems was photometrically, trying to map COMPAS systems, using various initial conditions for different binaries, onto the observable Gaia systems. For this, we needed a way to turn luminosities and temperatures—information COMPAS gives for each system— to magnitudes—information given for Gaia systems. Thus, I wrote a piece of code to do just that and a bit more.

My code allows the user to use any spectral distribution appropriate for the system being modelled. Once the spectral distribution is chosen, the user can choose the passband of the telescope being used, which is then convolved with the spectral distribution to obtain a flux for the system. Then, that flux is converted into the magnitude that the telescope would measure. Since Gaia has three different passbands: G, BP, RP, one can obtain the color of a star and its absolute magnitude and plot a color-magnitude diagram to see what sort of star it is.

To test this code, I ran a 1000-star COMPAS simulation, and using a black-body model, calculated their magnitudes with the Gaia passband filters. The plots below are color-magnitude diagrams of these COMPAS stars at different times in their evolution. Briefly, the stars all start off on the main sequence, as they should, and then begin to leave it, forming all kinds of non-main sequence stars. But what is more interesting, convincing us that the code is working well, is the path of the white dwarfs in the CMDs; white dwarfs do not undergo nuclear fusion, meaning that their temperature is always decreasing. If a star's temperature is decreasing, then its luminosity is decreasing as well, meaning that its magnitude decreases. In the CMDs you can clearly see the white dwarfs decreasing in absolute magnitude over time, consistent with what is expected. With these small checks, we can rest assured that the code works.

In practice, however, a black-body model will not be used; instead, a more detailed model is appropriate. In Fig. 8 we plot the spectral distribution of the sun using an atmospheric model—in this case the Castelli-Kurucz Atlas model—and the black-body model. For Gaia, the black-body model is an excellent approximation at higher wavelengths, but it starts to be less accurate in the lower wavelength regime. The reason for this discrepancy is that real stars have an atmosphere. This atmosphere tends to absorb high frequency photons and reemit them at lower frequencies, so the energy contribution from lower frequency photons is less than the higher frequency contribution. In Fig. 8 one can see that from 300 to around 400 nanometers, the blackbody overestimates the energy contribution, while from 450 to 700 nanometers the blackbody underestimates, reflective of the higher frequency photons being absorbed and reemitted as lower frequency photons. Fig. 9-11 show how the atmospheric model varies with temperature, metallicity, and surface gravity. At higher temperatures, the black-body model underestimates the spectral distribution of the sun, while at lower temperatures it overestimates it. Metallicity, a star's composition of elements that are not Hydrogen or Helium, seems to not change a star's spectral distribution much. The surface gravity of a star, however, does affect the amplitude of a star's spectral distribution, why is this so? Well, the surface gravity of a star is proportional to its mass, and the more mass a star has the more fuel it must burn, meaning that the more radiation it must emit. Why metallicity does not change the distribution much I really do not know, but why should metallicity affect it?

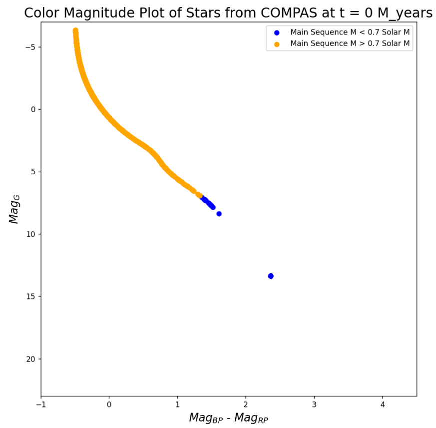

Fig. 2. CMD of COMPAS stars at time t = 0 million years

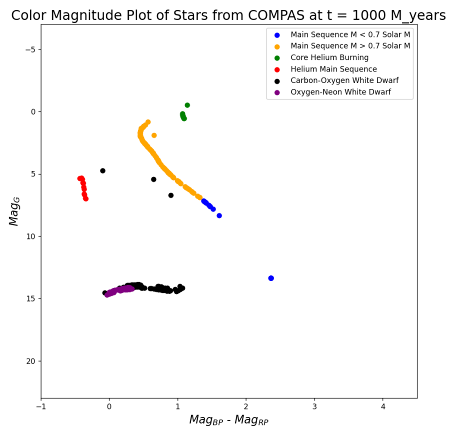

Fig. 3. CMD of COMPAS stars at time t = 1000 million years

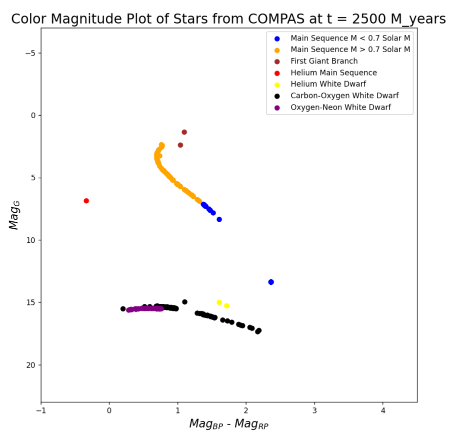

Fig. 4. CMD of COMPAS stars at time t = 2500 million years

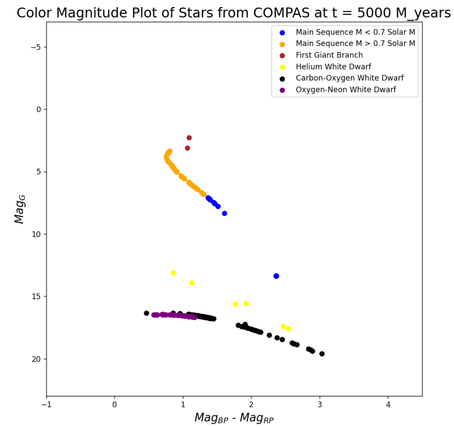

Fig. 5. CMD of COMPAS stars at time t = 5000 million years

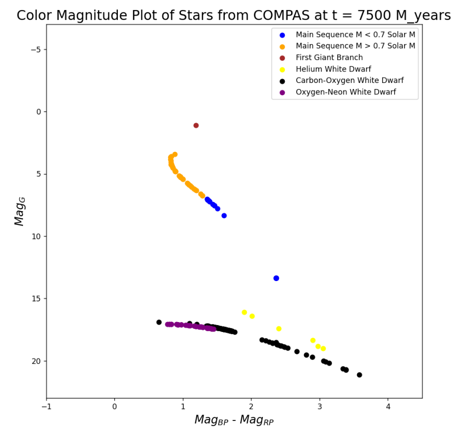

Fig. 6. CMD of COMPAS stars at time t = 7500 million years

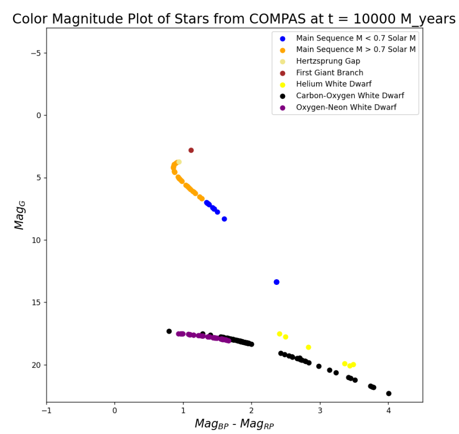

Fig. 7. CMD of COMPAS stars at time t = 10000 million years

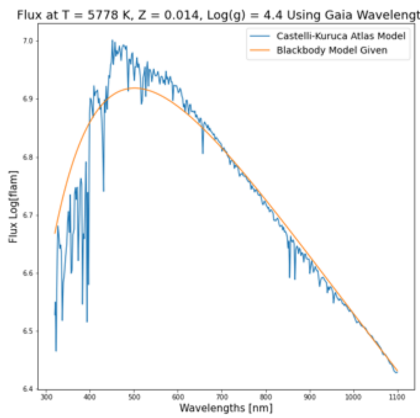

Fig. 8. Comparison of black-body and atmospheric model spectral distributions for our sun

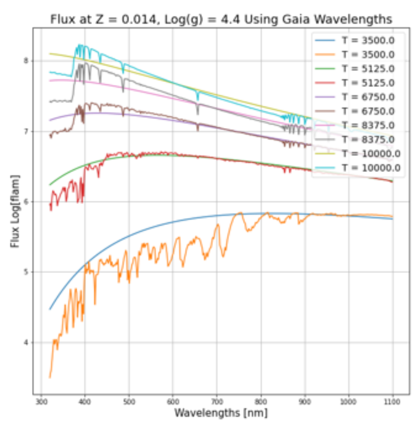

Fig. 9. Comparison of black-body and atmospheric model spectral distributions for our sun at different temperatures

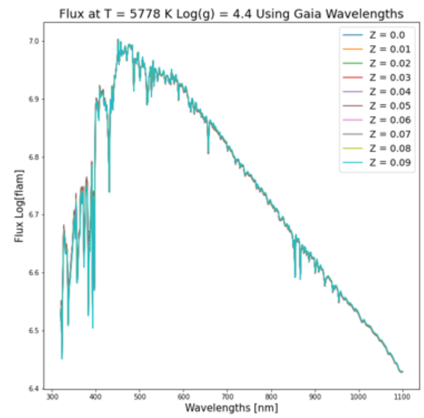

Fig. 10. Atmospheric model spectral distribution at varying metallicities

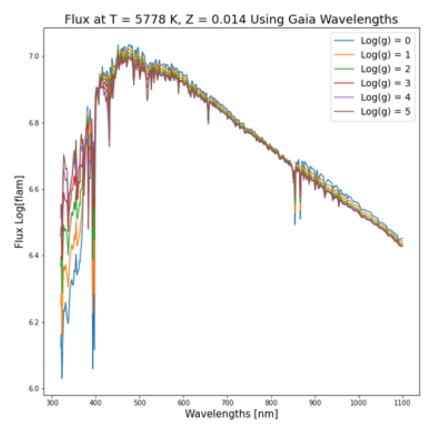

Fig. 11. Atmospheric model spectral distribution at varying surface gravities

4. Future Work

With tools in hand, we can now try to identify and characterize detached compact object binaries within Gaia data. The first Gaia catalog to look at was the ellipsoidal variable catalog by R. Gomel et.al, where they present 6306 possible compact object secondary candidates in ellipsoidal variables. Now, unfortunately my time at Monash University was coming to an end at the beginning of this phase, so I was unable to investigate the catalog all that much. The one investigation I was able to conduct was to see if there was some sort of white dwarf contamination in the catalog, at Ilya and Ryo's suggestion. For reasons I honestly do not know, the ellipsoidal variables in the catalog showed signs of having high roche lobe filling factors (my guess is that since ellipsoidal variables are shaped like an ellipse, the star is elongated at the equator, the roche lobe must be mostly filled), so the idea was to run a small COMPAS simulation with systems that had at least a 0.8 roche lobe filling factor (1 is the highest value and indicates mass transfer between the binary components) and see what sort of compact object secondaries arose. For this, I ran a 1000 binary system COMPAS simulation and obtained only those binaries with a compact object secondary and a main sequence primary that had a roche lobe filling factor of at least 0.8. From the 1000 binaries, 53 systems satisfied the criteria, and they all had white dwarf companions. Fig. 12 shows the primaries of the 53 systems on a CMD, on top of the CMD of the ellipsoidal variable catalog primaries.

So, running a small 1000 system COMPAS simulation, we obtained a few systems that had a primary satisfying the ellipsoidal variable condition and had a compact object secondary; all these systems resulted in having white dwarf secondaries. Does that mean that the ellipsoidal variable catalog could be contaminated with white dwarfs? That there are no neutron star or black hole secondaries? That Gaia is mainly sensitive to white dwarf systems? Or maybe COMPAS is wrong, why should we trust it? Well, I do not know. Those are questions we were left with. All I know is that, if the project is to be continued, more about Gaia needs to be known, specifically how they obtain their data and do their calculations, and better understand the selection effects.

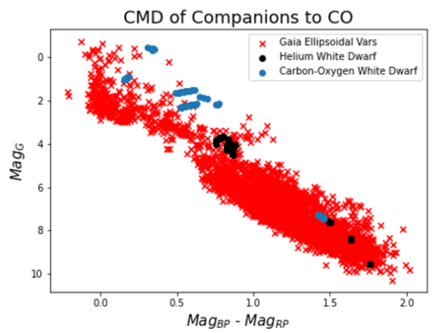

Fig. 12. Color-Magnitude diagram of main sequence secondaries showing possible white-dwarf contamination

5. Conclusion

The aim of the project was to identify detached compact object binaries within Gaia data and then characterize these systems to learn something about binary evolution with COMPAS. For this task, I developed a set of tools that calculate the color and magnitude of a star—or binary system—given a luminosity, temperature, spectral distribution, and pass band transmissivities for the specific telescope used. This code was then to be used on COMPAS systems to turn luminosities and temperatures—information COMPAS gives for each system— to magnitudes—information given for Gaia systems. Then, we would be able to run COMPAS simulations with varying initial conditions and attempt to obtain binaries with compact objects and primaries as observed by Gaia. Doing this, we would be able to generate statistics and determine what the compact object could most likely be and what the possible formation channels of the binary could have been.

Perhaps such a project would have never been possible to complete in a span of 8 weeks, by a mere undergraduate student; I really wish I could have finished it though. Nevertheless, I did have fun creating the tools for this project, I did learn more about astrophysics and would like to delve deeper. Overall, I would say I had a valuable experience during this program.

6. Acknowledgements

I would like to express my gratitude to Ryosuke Hirai and Ilya Mandel for all their help this summer; I asked so many questions, and honestly felt like a pest at times, but they were always willing and able to answer. Thank you, Paul Fulda, Peter Wass, Nathaniel Strauss, and Kathryn McGill, for organizing this program. Thank you to the National Science Foundation for providing the funding to this program through their grants NSF PHY-1460803 and NSF PHY-1950830.

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