

Central Compact Objects

A Senior Project

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by

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Section 1: Background

I. Introduction: What is a CCO?

Central compact objects (CCOs) are point-like sources found near the center of supernova remnants (SNRs). They emit X-rays with luminosities of 10^{33} to 10^{34} ergs/s (Pavlov et al. 2004), but show no radio or gamma ray counterpart. Furthermore, these X-ray emissions come from a radius on the order of ~ 3 km, much smaller than a typical 10 km neutron star radius; this makes them a curious astronomical phenomenon. CCOs have soft, thermal-like spectra much like an ordinary blackbody.

There are two types of nebulae associated with Type II supernovas. The first is the thin, hollow shell variety, comprised of debris pushed out at high velocities from the force of the supernova. The second is the twisting, filamented ball variety, which are created by young pulsars' electron winds passing through the magnetic field of the surrounding charged gas. These electrons passing through the magnetic field at nearly the speed of light causes them to emit radio waves, visible light, and X-rays in a process called synchrotron emission (Gaensler and Slane 2006). This second type of nebula is what is called a pulsar wind nebula. CCOs show no pulsar wind nebula. As such, one can conclude that CCOs are enclosed by nebulae of the first type. This, and the fact that they are found near the center of SNRs, are how we determine that CCOs form from the core collapse of a massive star. Consistent with this logic, theory suggests that most CCOs are either isolated neutron stars or black holes.

CCOs are an important frontier in astronomical study because they allow us to probe physics in extreme environments characterized by tremendously high densities (upwards of 10^{14} g/cm³), magnetic fields (10^{12} G), and temperatures (10^6 K). To probe these extremes, knowing exactly what we are dealing with becomes very useful. As such, my project was to look at two

known CCOs and see if I could construct a neutron star consistent with the observed CCO emission radii using known neutron star equations of state. In this paper, I will first discuss neutron stars and black holes, focusing on their observational properties. I will then give some background information on the specific CCOs I studied—Cassiopeia-A and Puppis-A—paying special attention to observational properties consistent with neutron stars and/or black holes. Finally, I will discuss the specific neutron star equations I explored—the Tolman–Oppenheimer–Volkoff relationship and Fermi Gas equations of state—and outline my attempts to construct neutron stars of particularly small radius.

II. Neutron Stars

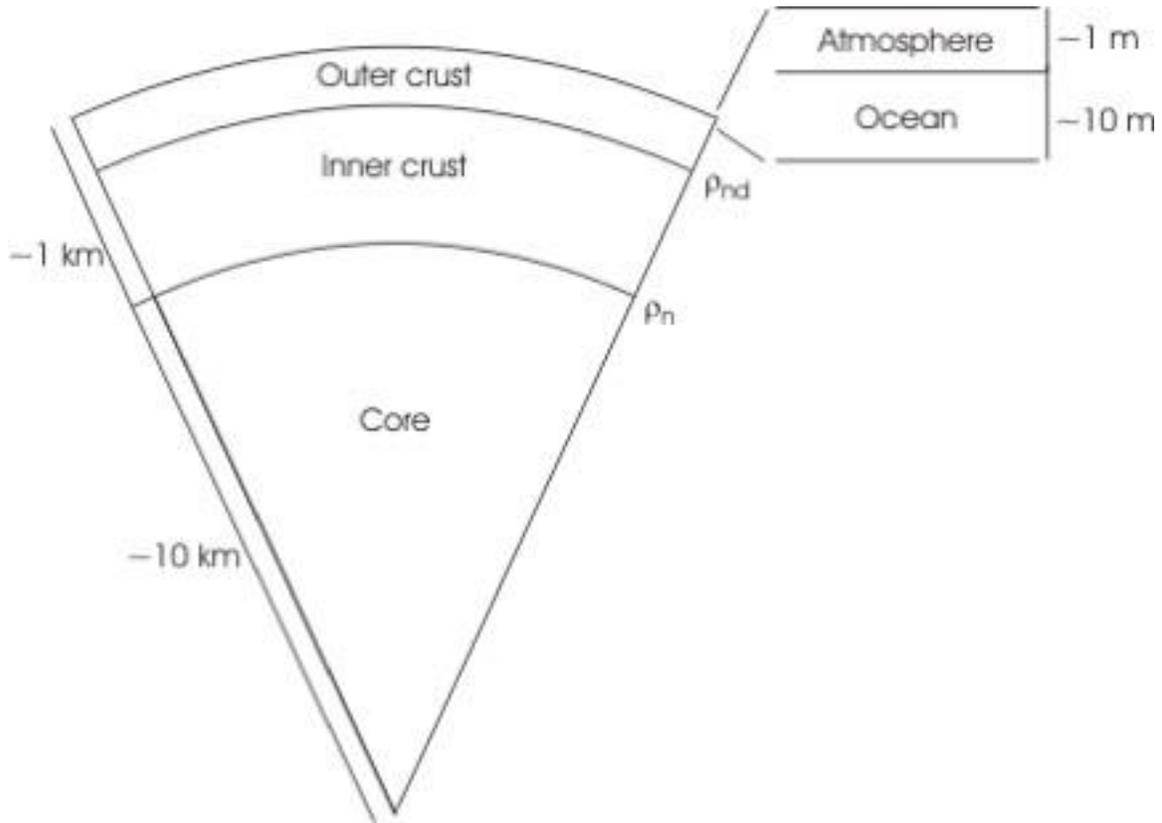
As stated above, one theory on the CCOs in observed SNRs is that they are isolated neutron stars. Stars spend most of their lives on the main sequence fusing hydrogen nuclei to form helium (alpha particles) in their cores. This fusion process serves the important purpose of creating radiation pressure to prevent a star from collapsing under its own gravity. From here, this fusion reaction continues until the hydrogen within the stellar core is depleted. As the core contracts, the temperature rises and heavier elements begin to fuse. A succession of reactions occurs: helium fusion (the 3α process), helium capture reactions, oxygen fusion, and so on until the stellar core consists of iron. Iron is special because it has the highest binding energy per nucleon. As such, both fusion and fission of iron *require* energy rather than releasing it. This causes the iron to build up in the stellar core. When the mass of this iron core exceeds $1.4 M_{\text{Sun}}$, the Chandrasekhar Limit, electron degeneracy in the core can no longer support the gravitational pressure, causing the core to rapidly collapse. As the core collapses, the least energetic path for the electrons and protons to take is to undergo a process called inverse beta decay in which a proton and an electron combine to form a neutron and a neutrino. Degeneracy pressure between

the neutrons prevents further collapse. As the star's in-falling upper layers hit the core, they rebound outwards. This explosion, known as a Type II supernova, blows away the outer parts of the star leaving the collapsed stellar core, now supported by neutron degeneracy pressure.

Neutrons are fermions (as are protons and electrons), particles that obey the Pauli Exclusion Principle. The Pauli Exclusion Principle states that no two identical fermions may occupy the same energy state of a system at the same time. In the extremely dense environment of a neutron star, each neutron wants to exist in the lowest energy state possible, filling up all of the available energy levels of the system. With no more space to move around, we say that the neutrons' positions are very well defined. Due to the Uncertainty Principle, an extremely well-defined position implies an extremely uncertain momentum (uncertainty Δp). On this scale, the momentum p is approximately equal to Δp . The momentum of the neutrons provides the so-called degeneracy pressure, which supports the neutron star from collapse.

Degeneracy pressure has a certain range of efficacy, which therefore dictates the maximum theoretical mass and radius of a neutron star. This maximum theoretical mass is called the Tolman-Oppenheimer-Volkoff limit, analogous to the Chandrasekhar limit for white dwarfs. Modern estimates show that neutron stars will have theoretical masses of $\sim 1.4 M_{\text{Sun}} \leq M_{\text{NS}} \leq 2 M_{\text{Sun}}$ (Thorsett and Chakrabarty 1999) and will have radii of approximately 10-15 kilometers, determined by the equation of state.

Figure 1: Neutron Star Composition
 (Credit: Dr. Michelle Ouellette)



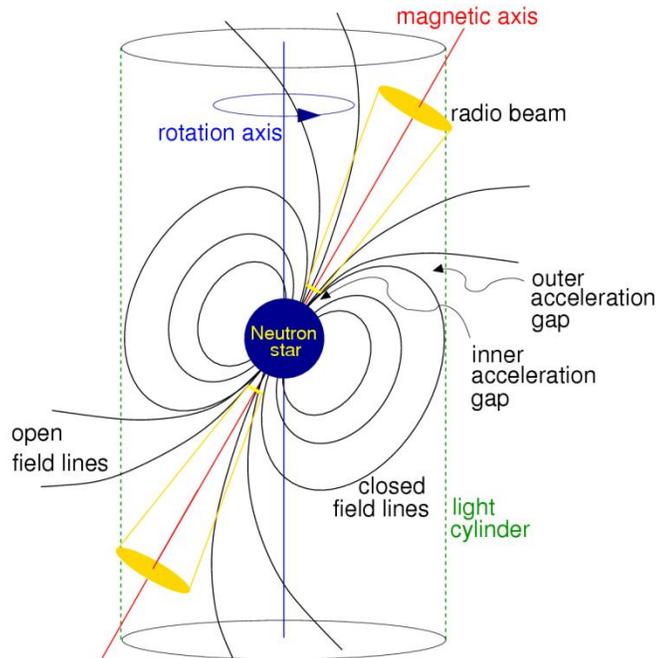
Neutron stars consist of: a surface, the outer crust, the inner crust, and the core. The surface of a neutron star has a density of $\rho \sim 10^6\text{ g/cm}^3$ and consists mostly of heavy atomic nuclei. The outer crust is a solid region with a density of $10^6\text{ g/cm}^3 \leq \rho \leq 4 \times 10^{11}\text{ g/cm}^3$, a thickness of $\sim 0.3\text{ km}$ and consists of primarily iron and free relativistic degenerate electrons. This upper limit on outer crust density comes from the density line for neutron drip, which is free neutrons "leaking" out of atomic nuclei. The inner crust has a density of $4 \times 10^{11}\text{ g/cm}^3 \leq \rho \leq 2 \times 10^{14}\text{ g/cm}^3$, a thickness of $\sim 0.6\text{ km}$ and consists of neutron rich nuclei, free relativistic degenerate electrons, and free superfluid neutrons. The upper limit on inner crust density is essentially where the equations of state cease to be well understood, making neutron star studies ideal for matter at extreme densities. The core has a density of $2 \times 10^{14}\text{ g/cm}^3 \leq \rho \leq 8 \times 10^{14}\text{ g/cm}^3$, a

thickness of ~10 km, and may consist of superfluid neutrons and smaller concentrations of superfluid protons and normal electrons. Finally, some equations of state predict a tremendously dense region with $\rho \geq 8 \times 10^{14} \text{ g/cm}^3$ where the pressure makes it possible for protons and neutrons to further break down into quarks or other particles such as pions, phonons, etc (Hledik 2002).

Two very unique properties arise from the conservations of magnetic field and momentum in neutron stars: extremely high magnetic field strength and rotational period. An average neutron star can have a rotational period as low as 1 ms. This is because angular momentum had to be conserved after the loss of mass due to the supernova, causing the stellar core remnant to rotate extremely fast. Neutron stars have magnetic field strengths of over 10^{12} G which interact peculiarly with these massive rotational speeds. At a certain distance from the neutron star, these magnetic field lines, rotating along with the star, would be moving faster than the speed of light. Since this is forbidden by special relativity, the magnetic field lines break and cause what is known as the lighthouse effect:

Figure 2: Pulsar

(Credit: http://www.cv.nrao.edu/course/astr534/images/PSRs_pulsar_sketch.png)



This lighthouse effect causes a stream of energetic particles to be emitted along the magnetic radius to conserve the magnetic field. These beams rotate along with the neutron star and sometimes align with Earth, giving a pulse each time the beam passes earth's field of view. This phenomenon is known as a pulsar and is only associated with the magnetic field of the solid surface of a neutron star. In addition, hydrogen burning on a neutron star surface generates tremendous X-ray bursts. These bursts are another observational signature of neutron stars.

III. Black Holes

As discussed above, the Type II supernova explosion of a star with a main-sequence mass between $8 M_{\text{Sun}}$ and approximately $15 M_{\text{Sun}}$ forms a neutron star. However, if the progenitor star mass is greater than $20 M_{\text{Sun}}$, the result is a black hole. When degeneracy pressure cannot prevent

a massive stellar core from further collapse, gravity takes over in full force, crushing all of that mass into an infinitely dense, zero volume singularity. A black hole is defined as an object from which nothing, not even light, can escape. The exact boundary within which the escape velocity is greater than the speed of light is called the event horizon of the black hole. The fact that not even light can escape a black hole implies that isolated black holes are completely undetectable by direct means. This gives rise to the paradoxical nature of black hole detection and the peculiarity of defining simple properties such as density, radius, and magnetic field.

The “no-hair” theorem states that stationary black hole solutions (in this case, stationary solutions refer to solutions with definite energies) can be uniquely characterized by only three characteristics: mass, charge, and angular momentum. In short, black holes can only be distinguished by these three properties (Mavromatos 1996). When dealing with observation, mass is by far the most pertinent of the three. At this point, it is important to introduce a very important property of black holes: the Schwarzschild radius. The Schwarzschild radius is the radius of the event horizon and can be derived from Newton’s laws of gravitation:

$$\text{Equation 1: } R_S = \frac{2GM}{c^2}$$

where R_S is the Schwarzschild radius, G is Newton’s gravitational constant, c is the speed of light and M is the mass of the black hole. The Schwarzschild radius is based solely on the black hole mass. This radius also allows us to define properties that before may have been peculiar for a black hole. For example, the volume of a black hole is technically zero while the density is technically infinite due to the fact that a black hole is a singularity. However, it is possible to define observational properties like volume and density using the Schwarzschild radius. The

volume of a black hole would be the volume of a sphere with a radius equal to the Schwarzschild radius and the density would be the mass enclosed divided by that volume.

One might ask, how is it possible to determine black hole mass observationally when a black hole, by definition, cannot emit light? The principle means for black hole detection is via their interactions with external matter, most importantly, gravitational interactions with other stellar bodies and matter accretion. These effects are most notable in binary systems with other stars. For black holes in binary systems, Kepler's laws can be used to determine the mass of the black hole via observable parameters such as the radius and period of the orbit. Gases from the binary companion star caught in the gravitational pull of the black hole form accretion discs. Friction between particles in the disc heats the material to very high temperatures. As well, this matter falls further into the black hole converting potential energy into kinetic energy. Both of these processes cause the radiation of energy, typically X-rays. This X-ray emission, along with gravitational interactions with other stars, are the only ways we have to detect a black hole.

IV. Identifying CCOs: Observational Properties

Leading theory, as mentioned in chapter 1, suggests that most CCO candidates are either isolated neutron stars or black holes. As such, carefully considering the observational properties of both help us to distinguish a CCO as one or the other. There are certain observations that can be made that will certainly and uniquely distinguish neutron stars from black holes. For example, an observed pulsar or X-ray burst certainly originate from neutron stars because they require a solid surface. Kepler's Laws can be used to determine masses of objects in binary systems. Those objects above the theoretical upper limit for neutron star mass are certainly black holes. However, we are concerned with CCOs which, by definition, do not occur in binary systems and are not pulsars. Thus, we have a completely unidentified, isolated object at the center of an SNR.

Neutron stars and black holes have very similar observed magnetic field strengths, luminosities, and blackbody temperatures:

Table 1: Typical NS and BH Values

Magnetic Field Strength	X-ray Luminosity	Blackbody Temperature
10^{12} G	10^{32} erg/s	10^6 K

The black hole luminosity and temperature refer to the X-ray emitting accretion disc. Therefore, the best properties we have to distinguish CCOs as either neutron stars or black holes are mass and radius, and even these can be problematic.

First of all, what do we mean when we refer to the radius of a black hole or neutron star? A neutron star has a well-defined surface and therefore radius, while a black hole technically has a radius of zero. The Schwarzschild radius can be used as the defined radius of a black hole and is dependant only on the mass. However, the *detectable* radius of either is the emission radius: the radius of the energy emission region of a particular source. However, when discussing black holes and neutron stars, it is useful to talk of the radius of the object itself, where the Schwarzschild radius is used for black holes. Typical values are shown in table 2.

Table 2: Mass and Radius Comparisons

Property	Neutron Star	Black Hole A	Black Hole B	Black Hole C
Mass	$1.4 M_{\text{sun}}$	$10 M_{\text{sun}}$	$5 M_{\text{sun}}$	$1 M_{\text{sun}}$
Radius	10-15 km	30 km	15 km	3 km

Black hole A is a typical black hole and is easily distinguishable from a neutron star due to its large mass. Black hole B is an observational troublemaker. Black holes like this one with masses

between 2 and 5 solar masses can have emission radii in the same range as neutron star radii, which make them extremely difficult to distinguish. Black holes like Black hole C are the ones my project is concerned with. Many CCO candidates have small radii in this 1-5 km range. The question is, if we observe a CCO with an emission radius this small, can we reasonably conclude that it is indeed a small stellar mass black hole? Or, is it possible with known neutron star equations of state to construct a neutron star that small?

V. Specific CCOs: The Cas-A and Pup-A CCOs

The Cassiopeia A (Cas-A) SNR is a famous remnant whose light reached Earth approximately 330 years ago (Aschworth 1980). The compact X-ray source at the center of Cas-A was discovered in a dedicated *Chandra* observation (Tananbaum 1999) and then confirmed to exist in reviewing archives of older *ROSAT* and *Einstein* observations. Pavlov et al. (2009) describe this remnant to be a "prototype of the so-called compact central objects (CCOs) in supernova remnants." The CCO has a radius of 0.20 to 0.45 km (Pavlov et al. 2000) with a bolometric luminosity on the order of 10^{33} erg/s (Pavlov et al. 2009) and fitting a blackbody thermal model yields a temperature of $(6-8) \times 10^6$ K (Pavlov et al. 2000). Aside from the radius, the rest of these properties are consistent with both black holes and neutron stars. Umeda et al. (2000) theorize that the CCO could be a black hole with an X-ray emitting accretion disc or a cooling neutron star. The radius of 0.20 to 0.45 km would seem to clearly suggest that the CCO couldn't possibly be a neutron star. However, Pavlov et al. (2002) have an alternate theory as to how this X-ray point source could originate from a neutron star. They postulate that the Cas-A point source is actually a localized hot spot on the neutron star surface whose surface temperature and magnetic field are nonuniform, making this hot spot stand out in the X-ray spectrum. Pavlov et al. (2009), further refine this theory, stating that the neutron star is an anti-

magnetar: a star with overall weak magnetic field relative to most neutron stars, 10^{11} G compared to the typical 10^{12} G. In this model, the CCO would be a point on the stellar surface with an extremely strong magnetic field, on the order of 10^{13} G, contrasted against the relatively low magnetic field of the anti-magnetar. This would create the observational illusion of a point source.

The Puppis-A (Pup-A) SNR is approximately 3700 years old (Winkler et al. 1988) and contains a unique CCO called RX J0822-4300, nicknamed the "Cosmic Cannonball." It earned this nickname by having an observed velocity of 1121.79 ± 359.60 km/s (Hui and Becker 2006). Pavlov et al. (1998) discuss observations of this CCO by the ROSAT X-ray satellite telescope. Like the Cas-A CCO, the Pup-A CCO has a blackbody temperature and luminosity consistent with both black holes and neutron stars, and shows a blackbody radius of approximately 2 km. Again, like the Cas-A CCO, this is far too small to be a canonical neutron star. Pavlov et al. (1998) come to the conclusion that this object may not be a CCO at all, just a regular radio pulsar whose radio-quiet nature and lack of a pulsar wind nebula may be due to unfavorable orientation of the pulsar beam with earth. Zavlin et al. (1998) conclude that the radius could be compatible with current neutron star models (~ 10 km) if the stellar surface were covered with a hydrogen/helium atmosphere but with an unusually high, but still canonical surface magnetic field strength (Zavlin, Pavlov, & Trümper, 1998a). Table 3 gives a summary of the properties of the two CCOs discussed in this section. Properties in the NS column indicate that these properties are consistent with known neutron stars. Properties in the BH column indicate that these properties are consistent with an X-ray emitting accretion disc belonging to a black hole. Properties in both columns are consistent with both neutron stars and black holes.

Table 3: Cas-A Properties

Property	NS	BH
Radius	X	0.20-0.45 km
Temperature	$(6-8) \times 10^6$ K	$(6-8) \times 10^6$ K
Luminosity	$(1.4-1.9) \times 10^{33}$ erg/s	$(1.4-1.9) \times 10^{33}$ erg/s
Mag. Field	10^{11} G	10^{11} G

Table 4: Pup-A Properties

Property	NS	BH
Radius	X	2 km
Temperature	$(1-5) \times 10^6$ K	$(1-5) \times 10^6$ K
Luminosity	$(1-2) \times 10^{34}$ erg/s	X
Mag. Field	3.4×10^{12} G	3.4×10^{12} G

Section 2: The Project

VI. Tolman–Oppenheimer–Volkoff Equation and Results

As a first step in constructing a neutron star model, I first created a neutron star pressure profile. The pressure at the surface of a neutron star is approximately zero and a rough estimate of the neutron star central pressure is approximately 10^{35} erg/cm³. This value needed to be estimated for this analysis because neutron star central pressure is highly dependent on the equation of state. Breaking this up into 400 steps gave me a pressure profile to use as an integration lattice for subsequent analysis. As described above, a neutron star is essentially a very dense gas of relativistic, degenerate neutrons. The equation of state relating the pressure of a relativistic, degenerate gas to density is

$$\text{Equation 2: } P = \frac{1}{4} (3\pi^2)^{1/3} \hbar c \rho^{4/3} N_A^{4/3},$$

where ρ is the gas density and P is the gas pressure, and all other values are traditional physical constants. The Tolman–Oppenheimer–Volkoff (TOV) equation is a simple analytic relationship between density and radius in a neutron star:

$$\text{Equation 3: } \rho(r) = \rho_c \left(1 - \left(\frac{r}{R}\right)^2\right)$$

where ρ_c is the central density and R is the total radius of the star. Substituting this into equation 2 and solving for radius gives

$$\text{Equation 4: } r(P) = R \sqrt{1 - \left[\frac{4P(3\pi^2 N_A^4)^{-1/3}}{\rho_c \hbar c} \right]^{3/4}}.$$

Using the Runge-Kutta method, I numerically integrated this equation over the span of the pressure profile. This gave a result of $r = 783$ km, well above the radius of even the largest neutron stars. This model shows that, given an input of a typical neutron star central pressure, a radius as small as those known CCOs is improbable. The error of this method comes from the fact that the equation for density depends on total radius, R ; refinements to this model are needed.

In an attempt to make some sort of conclusion, I looked at the basic Newtonian formulation of the TOV equation laid out in "Neutron stars for undergraduates" (Silbar and Reddy 2004). The standard formula relating mass to radius is:

$$\text{Equation 5: } M(r) = 4\pi \int_0^r r'^2 \rho(r') dr'.$$

Substituting in the equation for density outlined in equation 3, I integrated this for a neutron star radius of 10 km as a control, and again with a radius of emission of 3 km to simulate the small emission radius of a CCO. The 10 km radius gave a result of $0.7 M_{\text{Sun}}$, small for a typical 10 km radius neutron star, but this can most likely be attributed to this formulation being Newtonian, lacking corrections for relativity. The 3 km radius gave a result of $0.02 M_{\text{Sun}}$. This mass is far too small to be a neutron star. Even uncorrected for relativity, this model leads me to conclude that an object with a radius this small is most likely not a neutron star.

VII. Fermi Gas Equation of State and Results

The TOV equation is a good basic Newtonian formulation but is just an approximation. The use of an actual equation of state, an equation that relates state variables, is far more rigorous and makes for a better model. Specifically, I used the Fermi gas equation of state in the

framework of a polytrope to model the neutron star. This formulation assumes that a neutron star can be modeled as a Fermi gas, a collection of non-interacting fermions, and that this gas is a spherically symmetric polytropic fluid. A polytropic fluid is a fluid whose gravitational potential obeys the Lane-Emden equation:

$$\text{Equation 6: } \frac{1}{\xi^2} \frac{d}{d\xi} \left(\xi^2 \frac{d\theta}{d\xi} \right) + \theta^\gamma = 0$$

where ξ and θ are rescaled values of radius and temperature respectively, ξ is given by

$$\text{Equation 7: } \xi = r \left(\frac{4\pi G \rho_c^2}{(n+1)P_c} \right)^{1/2}.$$

In addition, the pressure in a polytrope depends on the density of the fluid via the relationship

$$\text{Equation 8: } P = K \rho^{1+\frac{1}{\gamma}},$$

where γ is the polytropic index, determined by the composition of the fluid and whether or not relativity is taken into account. K is a constant depending on relativistic considerations given by

$$\text{Equation 9: } K_{rel} = \frac{\hbar c}{12\pi^2} \left(\frac{3\pi^2 Z}{Am_N c^2} \right)^{4/3}$$

or

$$\text{Equation 10: } K_{nonrel} = \frac{\hbar^2}{15\pi^2 m_e} \left(\frac{3\pi^2 Z}{Am_N c^2} \right)^{5/3}.$$

These are reasonable assumptions for a neutron star model since neutron stars are made up of fermions, are reasonably spherically symmetric, and have pressures that depend on density at a

given radius. Using equations 20, 22, 25, and 33 in "Neutron stars for undergraduates" (Silbar and Reddy 2004), I obtained an expression for radius in terms of pressure:

$$\text{Equation 11: } r(P) = \sqrt{\frac{K\gamma}{4\pi G(\gamma - 1)}} \xi_1 \left[\frac{P^{1/\gamma}}{K^2} \left[\frac{1}{K} \left(\frac{R_0}{\alpha} \right)^\gamma \right]^{1-\gamma} \right]^{(\gamma-2)/2}$$

where G is Newton's gravitational constant, $R_0 = 1.47$ km (one half the Schwarzschild radius of our Sun), α is a fixed parameter used to tune the equation, and ξ is the constant defined by equation 7. Using the same pressure profile as the one used for the TOV calculations, I numerically integrated the radius equation with respect to pressure to obtain a value for the radius. For the nonrelativistic case, I calculated a value of $R = 1.0 \times 10^{-6}$ cm and for the relativistic case, I calculated a value of $R = 3.0 \times 10^{-2}$ cm. While my ultimate goal was to attempt to construct a neutron star model with a very small radius, these radii are orders of magnitude below even the smallest of CCOs and certainly orders of magnitude below any conceivable neutron star. Clearly, refinements are needed in the model, the code, or both.

VIII. Conclusion

Both of the models I constructed could use some refinements. My first analysis of the basic relativistic degenerate gas equation of state coupled with the density equation gave much too large a radius for a neutron star model. The TOV equation analysis could be further refined with corrections for relativity as shown in equation 5 of "Neutron stars for undergraduates." The polytrope model of the Fermi gas equation of state assumes that the neutron star consists only of neutrons and yielded a radius much too small for a neutron star model. While I suspect there are also issues in the code I wrote to analyze this model, the model itself could be further improved

by adding protons and electrons to the mix as well as taking the interactions between all of the nucleons into account.

I have demonstrated that distinguishing the neutron stars and black holes based on observational properties can be tricky. While my models only look at emission radius or mass, those properties are not always enough to conclude one way or the other. Pavlov et al. (2009) come to the convincing conclusion that the Cas-A CCO may in fact be a hot spot on a neutron star, explaining the small emission radius without the body itself being small. Pavlov et al. (1999) conclude that the Pup-A CCO could actually be a neutron star whose CCO properties—radio-quietness and lack of a pulsar wind nebula—may simply be due to unfavorable pulsar orientation with Earth. Zavlin et al. (1998a) conclude that the Pup-A CCO could be part of a neutron star surface with the rest of the star observationally obscured by the hydrogen/helium atmosphere. There is even a theoretical star model, an intermediate between a neutron star and a black hole, that allows for a $1-2 M_{\text{Sun}}$ to be contained in a body with a radius closer to those of the CCOs. This theoretical model is called a quark star. In the transition from iron core remnant to neutron star, at a certain pressure, it becomes energetically favorable for protons and electrons to combine to form neutrons, making up the material for the neutron star. In a similar fashion, it is theorized that at even higher pressures, it would become energetically favorable for the nucleons to separate into quarks, becoming an even denser fluid made up of quarks. If this occurred, it would be theoretically possible to have a star with the mass of a neutron star with a much smaller radius. The real conclusion I draw from my research on CCOs and modeling of neutron stars is that the question of identifying CCOs is much broader than simply neutron star vs. black hole. There are many theoretical models that can explain the small emission radii observed from CCOs that must be considered alongside all of the observational properties.

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