DILEMMA OF THE DEVIOUS DWARFS

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A scheme to weigh the Galaxy by tracing the orbital motion of distant stars was foiled recently by a number of dwarfs masquerading as giants. Dwarf stars, that is.

The Dark Matter

Main sequence stars, red giants, white dwarfs - these are three among the many types of stars that populate a galaxy. Our Sun is one among more than ten billion stars that make up our own Galaxy, the Milky Way. Does that mean the mass of the Galaxy is ten billion times the mass of the Sun? Strangely enough, our Galaxy, and all other galaxies that have ever been observed, contain much more mass than the sum of their visible parts. Astronomers have conclusively shown that matter in the Universe as a whole is more than 90% dark. Only 10% of the matter in the Universe is accounted for, and nobody yet knows what makes up the other 90%. The nature of the dark matter remains one of the most fundamental puzzles of modern astronomy.

How do we know there's so much dark matter if we can't even see it? We know because all matter, dark or not, exerts a gravitational force. If you measure the speed of rotation of stars around a galaxy, you have an indication of the mass of that galaxy. High speeds mean that the stars are tightly bound by a large gravitational force. Low speeds mean that the mass of the galaxy is relatively small. So the mass of a galaxy, including *both* light and dark matter can be estimated from the orbits of its visible stars. The visible matter (stars) can be used to 'weigh' *all* the matter.

The easiest place to measure the velocity of individual stars is in our own Galaxy. At the University of Washington, Seattle, Bruce Margon, Scott Anderson and I adopted a well-known ploy to measure its mass. The idea is to find a large number of very distant stars and measure their speeds. A star near the Sun, for instance, feels the pull only from the matter between here and the center of the Galaxy. If instead the stars we measure are very distant, then we can be assured that they feel the pull of most of the mass of the Milky Way so that the derived mass represents the total mass of the Galaxy. Ideally, these stars should be at distances comparable to the size of the Galaxy, which has a radius of about 75 thousand light years. One light year is the distance that light travels in one year, about 16,000 billion miles.

How do you find stars at such vast distances? The answer is to look for very faint stars, because if they're faint they must be far away, right? Not always. After all, the light from a 40 watt bulb only 10 feet away will be fainter than that from a 200 watt bulb 20 feet away. Like light bulbs, stars also come in many different brightnesses, so faintness alone is not a good distance indicator.

The Sun is a typical star, now in the main phase of its life, burning hydrogen in its core. When stars are on this 'main sequence', they are called dwarfs. But the Sun will eventually evolve into a giant star, increasing its brightness by more than 100 times. Many stars continue to evolve as giants, and begin to churn up the burnt material from deep inside, thus polluting their outer envelopes with their own waste products, like carbon, barium, strontium and even exotic, short-lived elements like technetium. Once a star has exhausted all its usable fuel, it can no longer keep its outer layers from collapsing. Most stars will then settle down into a dense, compact object called a white dwarf. Since a white dwarf is a collapsed object that has run out of fuel, it should not be confused with the main sequence dwarfs that are still burning hydrogen in their cores. White dwarfs are heated mostly by the gravitational collapse. They start out white hot, but since they have no fuel left to burn, over millions of years, they will simply cool off until they no longer emit light. So it's clear that stars can have a wide variety of 'wattages' (the astronomical term is luminosity).

It would be very handy for weighing the Galaxy if there were some kind of star that always had the same luminosity. When we started this project, everyone agreed that 'carbon stars' were always giant stars. A carbon star is marked by strong absorption due to carbon molecules of the light in its spectrum. A spectrum is obtained by spreading out a star's light as if through a prism. We measure the intensity of the resulting 'rainbow' at many wavelengths to determine if a star has the strong molecular features that characterize it as a true carbon star (see figure). Carbon is a product of nuclear burning in stars and should not be seen in the visible outer layers of a star unless the star is a giant, since *only* giant stars can dredge up processed elements like carbon from their cores. So if the theories of stellar evolution are right, carbon stars *must* be giants. Only one carbon (or 'C') star had ever been found to be a dwarf. This weird star, called G77-61, was assumed to be some kind of freak accident of nature and so was largely ignored by people hunting for dark matter.

Since they're virtually all giants, all that's needed to derive a reliable mass for the Galaxy is about 50 faint C stars. We just measure their velocities along the line of sight, and then we should be able to derive a good estimate of the mass of the Galaxy, dark matter and all. Velocities along the line of sight, called *radial* velocities, can be measured directly from the spectrum of a star. If the spectrum is shifted toward longer (redder) wavelengths, then the star is moving away from us. A blue shift means the star is moving closer. Whether toward or away, a larger shift means a larger velocity. This same 'Doppler shift' is a familiar phenomenon in everyday life, since the pitch of an ambulance siren is higher when it's approaching and then shifts to longer wavelengths (lower pitch) when the siren recedes.

To find 50 faint C stars is not an easy task because faint carbon stars are not very common. However, their colors are very distinctive due to the strong effects of the carbon molecules. Luckily, we already had a head start, since about 30 C stars had already been found using photographic plates. We opted instead to use 3 optical filters whose use was pioneered by Kem Cook at the Lawrence Livermore Labs in California, together with a CCD (a charge-coupled device). CCDs in astronomy are very similar to the chips found in the back of video cameras, only much more sensitive. Although this technique is particularly well-suited to finding carbon stars, it's difficult to cover a large area of sky with the small CCDs. Still, our CCD survey found dozens of faint candidates with the correct colors to be a C star. Our task was then to weed out the genuine C stars by obtaining their optical spectra.

Jumping Dwarfs

The telescope we used to collect optical spectra of previously known and candidate C stars from our CCD survey, the 84″ at Kitt Peak, Arizona, can point very accurately. We would just type the latitude and longitude of the star into the computer, and the telescope would whir along happily for a few seconds and then stop. Without exception the star would be just a tweak away from dead center on the telescope's TV screen. With less well-equipped telescopes, we normally need to consult a finding chart showing the stars in a wider area, with a little mark highlighting the star of interest. Of course we had these finding charts with us, but there was no need to consult them because of the excellent pointing accuracy of the telescope. If we had been forced to look at the finding charts, made from photographs taken in the 1950's, we might have seen that since the photograph was taken, one of the C stars had *moved* relative to the other stars around it.

The strange part of the story is that the star we were looking at was the 96th red star in the catalog of Peter Pesch and Nick Sanduleak. If we had looked at its finding chart, we would probably have figured out that the chart had been printed *upside down*, and attributed any confusion to that error. Why was this particular star's chart printed upside down and no other's? Draw the number 96 on a sheet of paper. Now turn the sheet upside down. It almost seems as if something out there was deliberately denying us the at-the-telescope, '*Eureka!*' sort of experience idealized in the more romantic views of astronomy. Who says occult numerology plays no role in science?

If we missed our chance at the telescope, how did we ever find out that the star moved? Peter Pesch, an astronomer at the Case Western Reserve University in Cleveland, pointed out to us that there was a star with a very similar longitude and latitude listed in a catalog of high proper motion stars. 'Proper' motion refers to stellar motion 'sideways', that is, perpendicular to the line of sight.

Since all stars orbit around the center of the Galaxy, they should all be moving, so what's so special about a proper motion? Imagine watching a speeding car. If you stand by the side of the road, the car whizzes by and spans your 180° of vision in a flash. If the road is a mile away, it might take 5 minutes for this sporty job to cover the same angle. If the car is a light year away and you watch it (you'll need a telescope), it will be a lifetime before the car would appear to move. But the fundamental premise of our technique for weighing the Galaxy was that faint carbon stars are distant giants. Therein lies the paradox: how could an extremely distant star be seen to move? The explanation must be that the star is *not* truly distant. It appears to be faint not because it's a distant giant, but because it's a star of much lower luminosity, a dwarf star. One dwarf C star, G77-61 might be a freak of nature, but two's company. Could there be a crowd of other dwarfs masquerading as giants?

Digging for Dwarfs

We went straight to the library and checked the proper motion catalogs for other faint C stars and immediately found another example. Together with the prototype G77-61, that made three carbon dwarfs. Then we noticed that several observers had measured the infrared colors of many C stars, using a standard set of filters. The three dwarfs had very different colors than most other C stars, but so did two or three other stars. Using a pair of photographic plates, one from the 1950s and one from the 1980s, Jack MacConnell at the Space Telescope Science Institute helped us to measure the proper motions of the odd-colored stars. Sure enough, they were also moving! This brought the total up to five.

The end result of our CCD survey is that we found only one new faint C star, so we were of no help in the struggle to weigh the Galaxy. If anything, matters only got worse when we realized that some unknown fraction of previously known faint C stars were actually dwarfs. You can't assume that C stars are giants - they may come in a thousand different luminosities, so that faint doesn't mean far anymore. One faint C star that had been assumed to be at a distance of 400,000 light years turns out to be only about 400 light years from here, and so not very useful for weighing all the dark matter in the Galaxy. Must we pronounce as dead the technique of using C stars to weigh the Galaxy ?

Well, clearly, it's possible to weed out the dwarfs that show large proper motions. But it's not always possible to find images of these stars separated by 30 years so that motions are large enough to be detectable, as was our good fortune. Furthermore, only some dwarfs will have orbits with sufficient velocity perpendicular to the line of sight to have measurable proper motions.

Happily, it appears that their strange infrared colors can be used to separate the dwarfs from the giants. So the weighing technique is rescued, but takes a bit more work than commonly assumed. In fact, it now appears to require almost as much work for carbon stars as for many other types of star. So now we're getting more interested in the dwarfs themselves. Instead of weeding them out, we need to *figure* them out.

Pondering a Polluted Paradigm

Since widely accepted theories of stellar evolution state that only giants can churn up enough carbon to visibly pollute their outer layers, how could a dwarf star show evidence for strong carbon? One clue had already been discovered in the prototype dwarf carbon (dC) star, G77-61. Although the star appears to be alone in the sky, the truth is that is has an invisible companion. This was discovered when it was found from to have a variable velocity, showing that it is in orbit around another nearby star. Such a stellar system is called a binary.

Nearly half the stars in the Galaxy are binaries - the Sun happens to be going it alone. The binary nature of G77-61 suggests that maybe the carbon in its outer layers *did* come from a giant star. But where's that giant now? The proposed scenario goes as follows: the dwarf and the giant were close enough so that the outer layers of the giant would have spilled over onto the dwarf, thus 'polluting' the dwarf with carbon and other pre-processed material. When a giant finally burns all of its fuel, it shrinks down to become a white dwarf. That white dwarf cools over many thousands of years, until the only star still visible is the newly carbon-rich dwarf. This so-called 'mass transfer scenario' seems to be a reasonable evolutionary path that could explain all the dC stars.

This scenario may rescue the standard models of stellar evolution, but only if we can show that *all* dCs have companions. Furthermore, some dCs should have white dwarf companions still hot enough to be visible. One such system was discovered in the same year we published the much-lengthened list of new carbon dwarfs.

PG0824+289 was originally found by its very blue colors. A spectrum of its blue light shows that it is a hot white dwarf star. A spectrum of its red light looks more like a carbon star. It's not one star, but rather a white dwarf + dC binary. Here is a visible confirmation of the mass transfer theory. Even more tantalizing is the sharply peaked emission lines seen in the spectrum of PG0824+289. Such emission lines are known only in a few binary systems where the two stars are so close that the white dwarf strongly heats the atmosphere of its main sequence companion. PG0824+289 may well be close enough that mass transfer *had* to occur.

At this writing, there are seven other dwarfs known from a variety of sources. Although the mass transfer scenario now looks very promising, for dCs with no companion visible, we must show that most if not all have detectable velocity variations. If the formerly giant companion is no longer visible, then radial velocity variations are the only way to prove that the dC is indeed in a binary system that might have undergone mass transfer.

We are currently obtaining a series of measurements of the Doppler shifts of dCs from their optical spectra to search for radial velocity variability. An added benefit of these spectra is that we can also use them to study the composition of the 'pollutants' to try to understand the nature of the now extinct companion stars. There are hints from the spectrum of G77-61 that it may be one of the oldest types of stars in the Galaxy. Even if their giant companions have now faded, we may still be able to use G77-61 and other dCs to understand better the long-dead first generation of giant stars in the Milky Way.

Epilog

There are several thousand carbon stars known in our Galaxy, but most of them are very bright, and surely giant stars. Since now eight carbon dwarfs are known, their existence can no longer be shrugged off as a 'freak accident'. The likely reason that there are thousands of known C giants and only eight known C dwarfs is that the giants are thousands of times brighter and therefore much easier to find. By comparing the apparent brightness of a star to its intrinsic luminosity, we can estimate distances for both dwarfs and giants. This is like knowing whether we have a 40W or a 150W bulb, and then estimating the distance to the light bulb by how bright it appears. Because they are so faint, the furthest distance at which carbon dwarfs have been seen is about 1200 light years. Within that same distance, there are only a couple of dozen bright carbon giants known, with the other thousands of C giants much further away. Astronomers have surely found a much smaller fraction of all the C dwarfs in our neighborhood as they have of the C giants, since the latter are about ten thousand times as bright. So unless the volume of space 1200 light years across that surrounds the Sun is unique, the true number of dwarf C stars in the Milky Way is probably greater than the number of C giants.

The discovery that many C stars are dwarfs means that astronomers must determine whether a C star is a dwarf or giant. This complicates the technique of using carbon stars as orbital tracers of the Galactic mass. At the same time, it opens the door wide on new fields of stellar and Galactic evolution. Mass transfer binary systems once thought to be an exotic exception may turn out to be as common as mud. That gives us a better chance to understand another facet of what seems to be an occasionally rather devious Universe.