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Discovering Hypervelocity Stars: Speed-demons of the Milky Way

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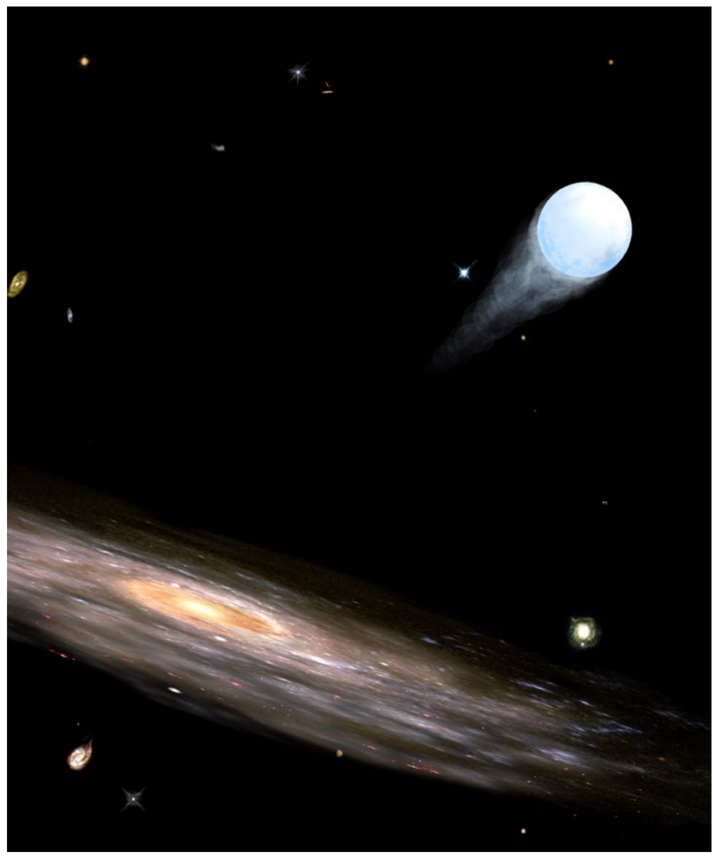
Editor's Introduction

It's not often that astronomers find a whole new population of stars with unexpected characteristics. But that's exactly what Warren Brown did when he found stars moving away from our Galaxy at spectacular speeds. We asked him to recount the story and the implications of his discovery for our readers.

Over the past few years I've measured the motions of stars in the distant outskirts of the Milky Way and discovered the most amazing thing: some stars moving away from us at 1–2 million mph. These speeds are absurd. No star in the Milky Way (outside of the Galactic center) moves that fast, and for a very good reason. A star moving 1–2 million mph very quickly escapes the Milky Way. Equally remarkable, these are short-lived stars. Although they must have formed recently in the Milky Way, the stars are now 100,000's of light years away in the empty depths of space. To explain these stars requires something extreme.

Black holes are the most compact objects in the Universe, and astronomers believe that a massive black hole lurks in the heart of our own Milky Way galaxy. While a black hole can never be seen directly, its presence can be revealed by the motions of stars around it. Stars crowd together in the center of the Milky Way, and some of them have been seen moving



Artist's impression of a hypervelocity star leaving the Milky Way
(Courtesy Harvard-Smithsonian Center for Astrophysics)

a few percent of the speed of light as they orbit around the very center of the Galaxy. These orbits betray the gravitational pull of a mass of 4 million Suns. Yet the tiny region at the center of the Galaxy does not contain 4 million shining Suns; it contains nothing visible except for the point source of radio waves that we call SgrA*. The simplest explanation for all the observations is that a 4 million solar-mass black hole sits in the heart of the Milky Way.

Back in 1988 — a decade before astronomers had built infrared cameras capable of peering into the heart of the Milky Way and seeing the stars that orbit there — astronomer Jack Hills predicted that the signature of a massive black hole would be the ejection of "hypervelocity stars."

Hypervelocity star ejections actually require three objects. Why? Two objects will happily orbit around each other forever, but if you add a third object, then you can exchange energy between them. If one of those objects is a massive black hole, you can exchange a lot of energy. In the case of a black hole that disrupts a pair of stars, the star that loses energy is captured into a tight orbit around the black hole, and the other star, by conservation of energy, is slung outward. Because stars move a few percent of the speed of light near the black hole, the final velocity of the ejected star can be millions of mph, a velocity in excess of the escape velocity of the entire Milky Way galaxy.

Hypervelocity star ejections are rare, however. Jack Hills and other theorists estimate that the Milky Way's central black hole ejects a hypervelocity star about once every 10,000 years. That means, of the Milky Way's few-hundred billion stars, there are perhaps a thousand hypervelocity stars escaping the Milky Way today. Surveys of stars near the Sun have not found a hypervelocity star because hypervelocity stars are simply too rare. In fact, seventeen years passed between when Hills predicted hypervelocity stars and when I found the first hypervelocity star in 2005.

The story of the discovery of the first hypervelocity star begins when I finished my PhD in 2002 and was pondering what project I might do with the newly upgraded 6.5m MMT telescope. With the encouragement of Dr. Margaret Geller and Dr. Scott Kenyon at the Smithsonian, I proposed a project to measure the motions of old, evolved blue stars in the distant outskirts of the Milky Way halo. By distant I mean 250,000 light years distant. My goal was to use the motions of these distant stars to measure the total mass of the Milky Way galaxy, a fundamental but poorly known quantity. I also hoped to discover streams of stars moving together — proof that (former) dwarf galaxies have merged with our own Milky Way. The remnants of these small, captured galaxies should be visible as stars orbiting together in the outer parts of the Milky Way. The observations were straightforward. Blue stars are easy to identify by their color, so all I had to do was measure their motion using the MMT spectrograph.

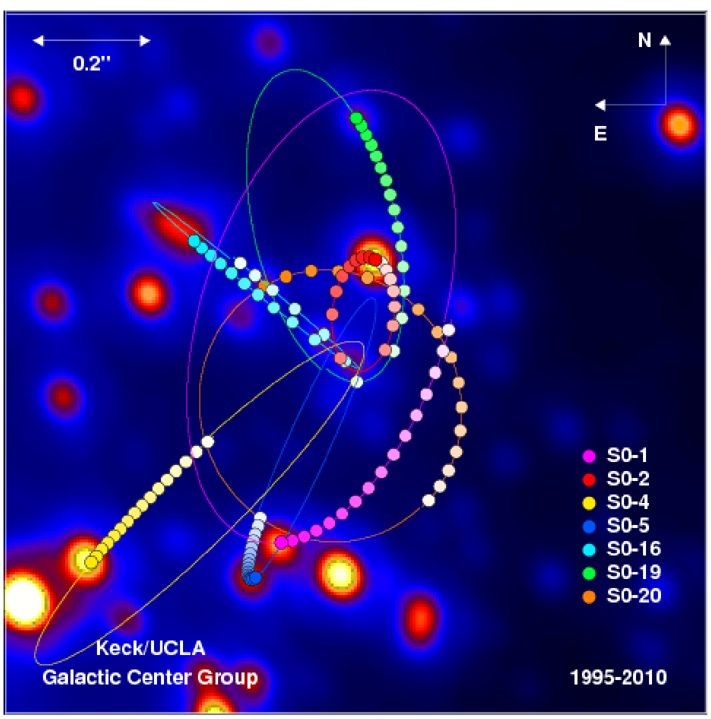
Center of the Milky Way Galaxy seen in the Infrared. In this remarkable false-color image from the Spitzer space telescope, we see the central section of our Galaxy, showing a horizontal span of 890 light-years and a vertical span of 640 light-years. *(NASA/JPL-Caltech/S. Stolovy/Spitzer Science Center)*

Telescopes allow us to collect the light of very faint stars, but it is spectrographs that allow us to measure the stars' physical properties. A spectrograph works by dispersing the light of a star into a rainbow spectrum and then taking a picture of that rainbow spectrum. Atoms in the atmosphere of a star absorb light at very specific wavelengths and thus produce a distinctive fingerprint in the spectrum. But just as sound waves from an ambulance siren have a higher and then lower pitch as the ambulance moves first towards and then away from you, so will a star's spectral lines be Doppler shifted to shorter or longer wavelengths if it is moving towards or away from you. Thus I can tell a star's line-of-sight motion by measuring the shift of its spectral lines. I was doing these types of measurements when I discovered the first hypervelocity star in 2005.

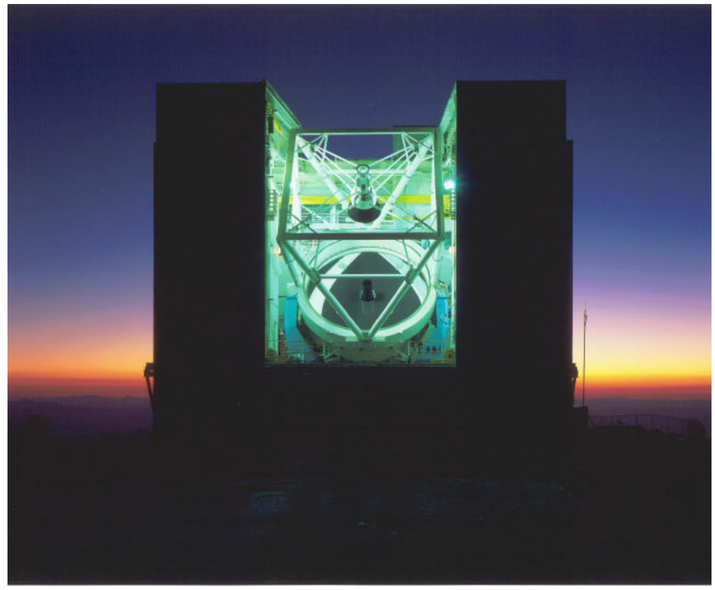
Finding such a fast-moving star was exciting, because its very existence is another piece of evidence that a massive black hole must exist in the Milky Way. Finding more hypervelocity stars would be even more exciting, because the properties of hypervelocity stars are linked to the black hole that ejects them. For example, a pair of massive black holes in the center of the Milky Way could easily eject single stars as hypervelocity stars, but preferentially from the orbital plane of the pair of black holes. Thus you would see a ring of hypervelocity stars around the sky. And the closer the pair of black holes orbit together, the more energetic the hypervelocity star ejections would be. This is a very different pattern of positions and velocities than is produced by a single black hole, which can eject hypervelocity stars any time and in any direction. This distinction means, in other words, that hypervelocity stars can tell us if a pair of massive black holes are spiraling inward towards each other in the Galaxy's center.

To test these ideas, I designed a targeted survey to find more hypervelocity stars. The survey strategy is threefold. First, because hypervelocity stars are rare, I targeted luminous stars that I can see over a large volume of space. Second, because there are very few normal stars in the distant outskirts of the Milky Way, I maximized the contrast between normal stars and hypervelocity stars by observing the outer parts of the Milky Way. Finally, I targeted short-lived "B-type" stars, stars which should not exist in the outskirts of the Milky Way...unless they were ejected there.

The Hypervelocity Star Survey worked. Over the past five years I have been able to announce the discovery of 14 unbound stars. They are all moving away from us (we have not found a hypervelocity star moving towards us), consistent with the picture that these are stars being ejected out of the Milky Way. Follow-up observations of the 4 brightest ones establish that the hypervelocity stars are short-lived B-type stars, just as I thought.



Map of SgrA*, the center of our Galaxy, showing the orbits of fast moving stars that allow us to measure the mass of the central black hole.



The MMT Telescope in Arizona. The hypervelocity star discoveries were made with the 6.5m MMT telescope.

Knowing the distance and velocities of the hypervelocity stars, I can calculate their travel times from the Milky Way. If I am right about their origin, then the hypervelocity stars' travel times reveal the ejection history of stars from the central black hole. The travel times appear evenly spread over the past couple hundred million years. Thus it appears that the Milky Way does not have a pair of black holes that have spiraled together in the Galactic center in the past couple hundred million years, or at least not so that produced a burst of hypervelocity stars.

One unexpected discovery is that most hypervelocity stars are found around the constellation Leo; they are not randomly scattered over my survey region. There are a number of proposed explanations for this, such as hypervelocity stars coming from the stellar disks circling the central black hole, hypervelocity stars coming from a binary black hole, or hypervelocity stars coming from a tidally disrupted dwarf galaxy. Each explanation predicts a different distribution of hypervelocity stars on the sky. To answer this question, I will next search the southern hemisphere for hypervelocity stars, in collaboration with the Australian Sky Mapper survey, and determine the all-sky distribution of hypervelocity stars.

Right now I am using the Hubble Space Telescope to measure the hypervelocity stars' proper motions — their motion on the plane of the sky. With proper motions I can determine the stars' trajectories and where they come from. I published the first proper motion result last year for the hypervelocity star near the Large Magellanic Cloud. Astronomers thought that this hypervelocity star must come from the Large Magellanic Cloud, but the Hubble Space Telescope proper motion showed that the star in fact comes from the center of the Milky Way. Ultimately, we hope to use the proper motions of all the hypervelocity stars to map out the Milky Way's dark matter. If the Milky Way is surrounded by dark matter, then the hypervelocity stars' trajectories must deviate from the Galactic center, and this deviation is a measure of the Galaxy's dark matter distribution. I hope to complete our Hubble Space Telescope program next year.

I hope I have shown you that hypervelocity stars are not just celestial oddities; they are important because their properties link to the nature of the black hole that ejects them, and their trajectories may measure the Milky Way's dark matter distribution. There are so many more discoveries yet to be made that the future of hypervelocity stars appears...unbound.

About the Author

Dr. Warren R. Brown is an astronomer at the Smithsonian Astrophysical Observatory. He is best known for his Hypervelocity Star Survey, but he also leads a targeted survey for merging pairs of white dwarfs that are currently the strongest known sources of gravitational waves and that may one day explode as supernovae. Dr. Brown directs the Smithsonian's Telescope Data Center and is heavily involved in building new instruments for ground-based telescopes. He is Principal Investigator for the Smithsonian Widefield Infrared Camera, co-PI of the MMT Magellan Infrared Spectrograph, and Project Scientist of the proposed Giant Magellan Telescope Near Infrared Multi-Object Spectograph. Dr. Brown grew up in Sacramento, CA, earned his B.S. from the University of Arizona, and his Ph.D. from Harvard University.

Resources for Further Information

Dr. Brown's web site at the Harvard-Smithsonian Center for Astrophysics is:
https://www.cfa.harvard.edu/~wbrown/

Sky & Telescope magazine news story about the hypervelocity star near the Magellanic Clouds:
http://www.skyandtelescope.com/news/100993774.html

Hubble news release on one hypervelocity star where the proper motion was measured:
http://hubblesite.org/newscenter/archive/releases/2010/2010/19/ ✦