Using Gravity to Measure the Mass of a Star

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Abstract

In a reprise of the famous 1919 solar eclipse experiment that confirmed Einstein's general relativity, the nearby white dwarf, Stein 2051 B, passed very close to a background star in March 2014. As Stein 2051 B passed by, the background star's position was relativistically deflected. The superb angular resolution of *Hubble* allowed us to measure this deflection—the first such measurement of the deflection caused by a star beyond the solar system—and thereby determine the mass of Stein 2051 B. This mass measurement confirms the physics of degenerate matter, and provides a new tool to determine the masses of isolated stars.

Measuring mass through relativistic deflection

One of the key predictions of general relativity set forth hundred years ago by Einstein was that the curvature of space near a massive body causes a ray of light passing near it to be deflected by twice the amount that would be expected based on classical Newtonian gravity (Fig. 1). The first observation of this phenomenon came during the total solar eclipse of 1919, providing one of the first convincing proofs of general relativity. Yet, despite 100 years of technological advances, this phenomenon had not been observed beyond the solar system—not surprisingly, because the deflections are so tiny. Even for the nearest stars, the angular deflection is two to three orders of magnitude smaller than the deflection of 1.75 arcsec measured during the 1919 solar eclipse.

The relativistic deflection depends on the mass of the deflecting object (lens), the angular separation between the lens and the source, and the parallactic distance of the lens with respect to the source. Since the angular separation and the paralactic distance can be measured accurately, the relativistic deflection provides a direct measure of the lens mass. Unlike classical methods involving binaries, this method can be applied to mass measurements for single stars.

Predicting close encounters of the stellar kind

Close passages of stars in front of background stars, however, are very rare. So we carried out a large-scale search for such events in which nearby stars with large proper motions (PMs) would pass closely in front of background sources. One of the most interesting predicted events was a close passage of the nearby white dwarf (WD) star Stein 2051 B in front of an 18th magnitude background star. We estimated that the closest encounter would occur during March 2014, with an impact parameter of 0.1 arcsec. Actual measurement of such a deflection, especially so close to the glare of the bright foreground star, is challenging but within the capabilities of the instruments on the *Hubble Space Telescope*.

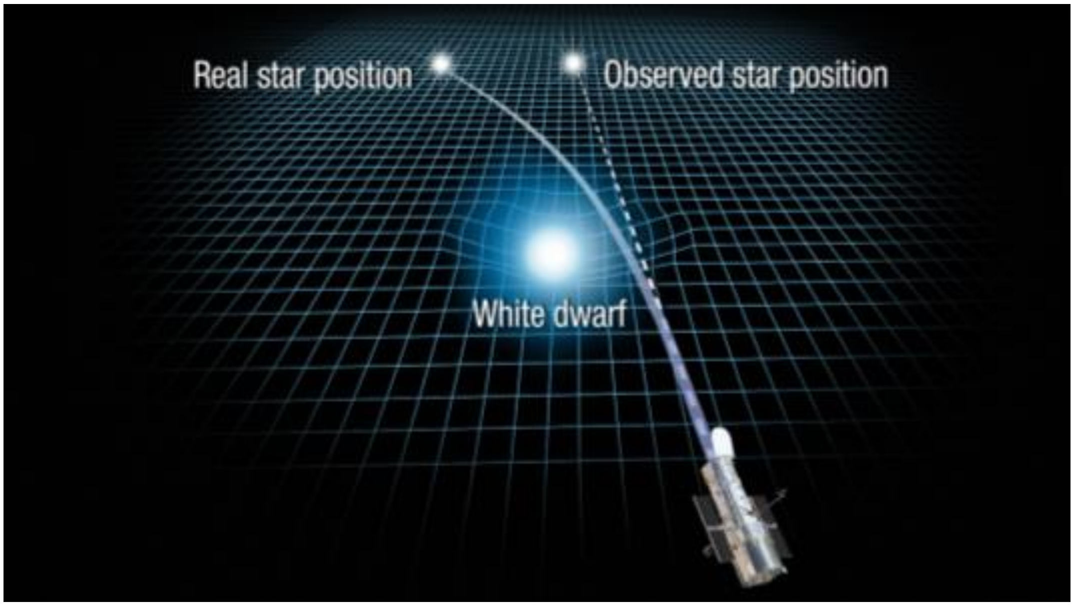

Figure 1: A shematic representation of the relativistic bending of light. The curvature of space near the white dwarf bends the light rays from the distant star, causing an apparent shift in the position of the distant source.

The cool and nearby white dwarf Stein 2051B

Stein 2051 is a nearby visual binary whose fainter (V = 12.4) but more-massive component, Stein 2051 B, is the sixth nearest white dwarf at a distance of 5.2 pc. The brighter, 11th-magnitude companion, Stein 2051 A, is a low-mass, main-sequence star of spectral type M4. The angular separation between the two components is currently ~10.1arcsec.

The actual mass of Stein 2051 B has been a matter of debate. Photographic observations extending back to 1908 have been used to measure orbital motion, from which the mass of B was estimated to be 0.50 $M_{\odot}$. To explain its observed radius, such a low mass would require the WD to have an iron core, which would be in conflict with normal theory of stellar evolution. Moreover, a WD cooling age of ~2.0 Gyr derived for Stein 2051 B, combined with the implied long main-sequence lifetime of the progenitor of a low-mass WD, would give the system a total age uncomfortably close to the age of the Universe.

Measuring Deflections with Hubble

We imaged the field of Stein 2051 with the Wide Field Camera 3 at eight epochs between October 2013 and October 2015 as shown in Figure 2 (Sahu et al. 2017). The figure shows a color image of the region around Stein 2051 B, created by superposing F606W and F814W frames at the first epoch. The path of the WD past the source, due to PM and parallax, is depicted by the wavy line. Closest approach to the source star occurred on 5 March 2014, at an angular separation of 103 milliarcsec. We used the observations at all eight epochs to determine the parallax and PM of the WD, and observations at 4 epochs for the deflection analysis.

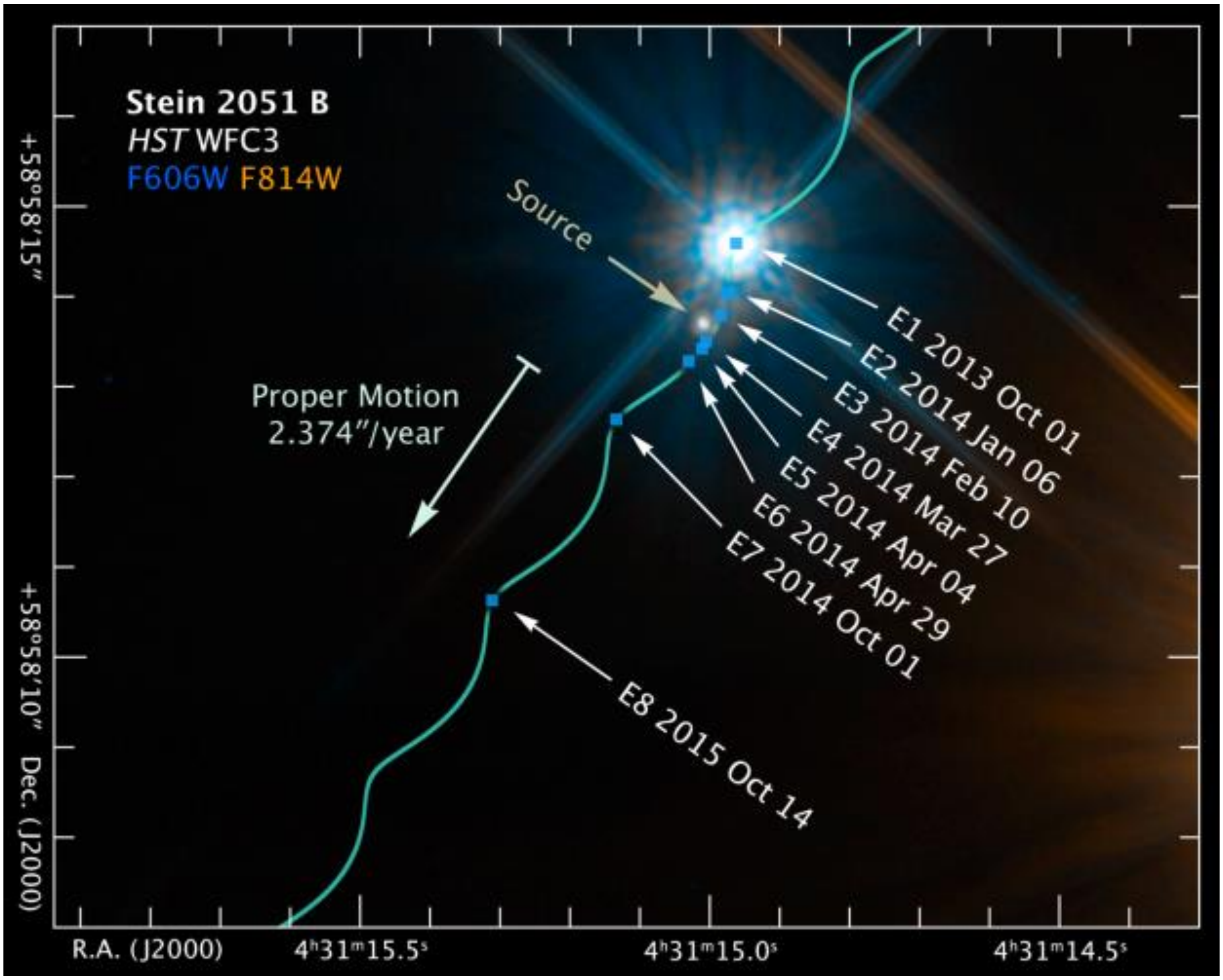

Figure 2: *Hubble Space Telescope* image showing the close passage of the nearby white dwarf Stein 2051 B in front of a distant source star. The path of Stein 2051 B across the field due to its proper motion towards south-east combined with its parallax due to the motion the Earth around the Sun, is shown by the wavy cyan line. The source is also labelled.

Figure 3 plots the measured source positions at the four epochs we analyzed, showing the relativistic deflections, to which we performed a model fit. The resulting fitting parameters indicate an Einstein ring radius of $\theta_E = 31.53 \pm 1.20$ mas, corresponding to a mass of $0.675 \pm 0.051\ M_\odot$.

Mass of Stein 2051 B and the MRR

Most stars end their lives as WDs—as will the Sun—and then slowly cool. Composed of degenerate matter, WDs are expected to obey a mass-radius relation (MRR) such that, as the mass of the WD increases from ~0.5 $M_\odot$ to the Chandrasekhar limit of ~1.4 $M_\odot$, its radius decreases approximately as the inverse cube root of its mass. However, observational confirmation of MRR is rare since the vast majority of WD masses cannot be measured directly, but have to be inferred using theoretical models.

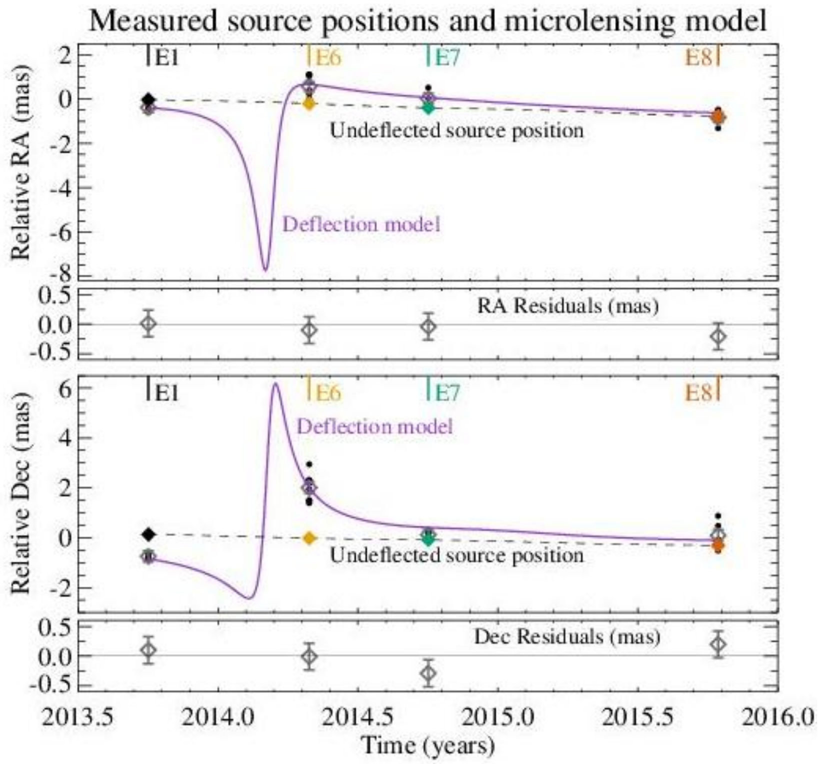

Figure 3: Our measured and the model positions of the background source as a function of Time**.** Solid diamonds show the undeflected positions. The measured deflected positions are plotted as filled black circles, their mean at each epoch is shown as a diamond. The model fit (solid purple curve) has an Einstein ring radius of 31.53 milliarcsec.

Our direct measurement of the mass of Stein 2051 B provides a direct confirmation of the theoretical MRRs. The location of Stein 2051 B in the MRR is plotted in Figure 4, which shows an excellent agreement with the theory. For comparison, the MRR for zero-temperature WDs with iron cores is also shown, which is excluded by our measurement, thus putting the 100-year old debate to rest.

Future Prospects

The single most important physical parameter of a star is its mass. The mass of a star dictates its temperature, radius, luminosity, lifetime, and ultimate fate. Yet, we do not have a model-independent method to measure the mass of a single star. The method described here provides a direct, model-independent method, in those favorable cases of a nearby star fortuitously passing close in front of a background source. Unlike classical methods involving binaries, this method can be applied to mass measurements for single stars. We have another ongoing *Hubble* program to measure the mass of the nearest star, Proxima Centauri, using this method. Finally, there are several future missions, such as *Gaia*, LSST and *Webb*, which will have sufficient astrometric accuracy to perhaps provide direct measurements of many single stars through this method.

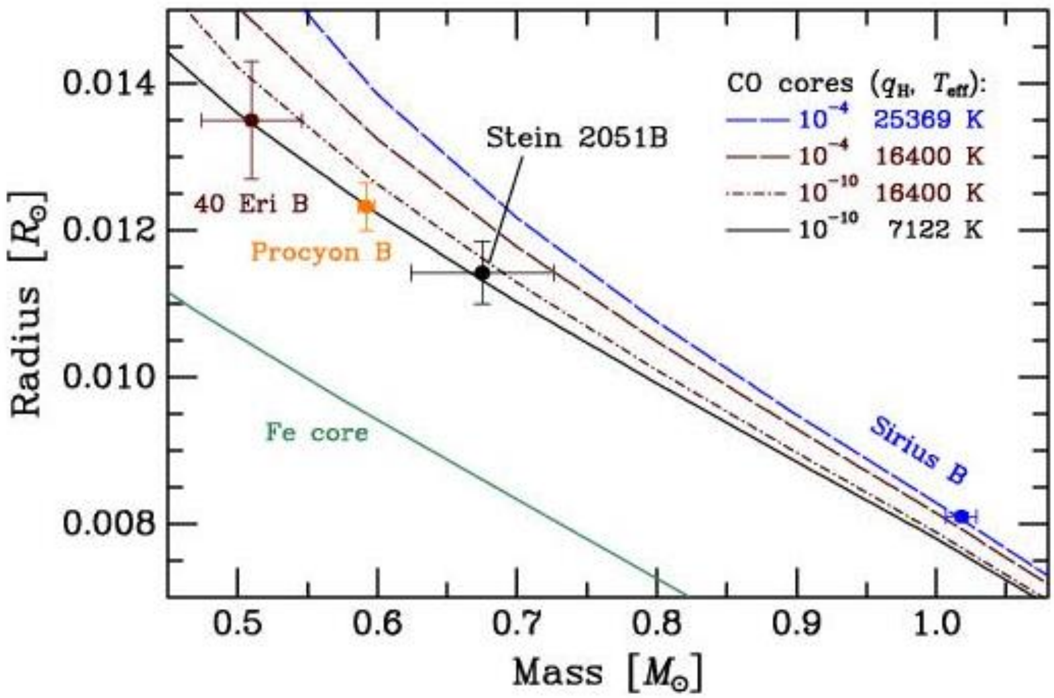

Figure 4: Mass-radius relation for Stein 2051 B and only three other nearby white dwarfs in visual binaries for which the masses have been independently determined. The black curve is a theoretical mass-radius relation for carbon-oxygen core white dwarfs with the parameters of Stein 2051B. The mass of Stein 2051 B inferred from the astrometric microlensing, 0.675 ± 0.051 $M_\odot$, falls right on the theoretical MRR, thus providing a confirmation of the theory of white dwarfs.

References

Sahu, K. C., et al. 2017, Science, 356, 1046