Testing Einstein with the 2017 Total Solar Eclipse

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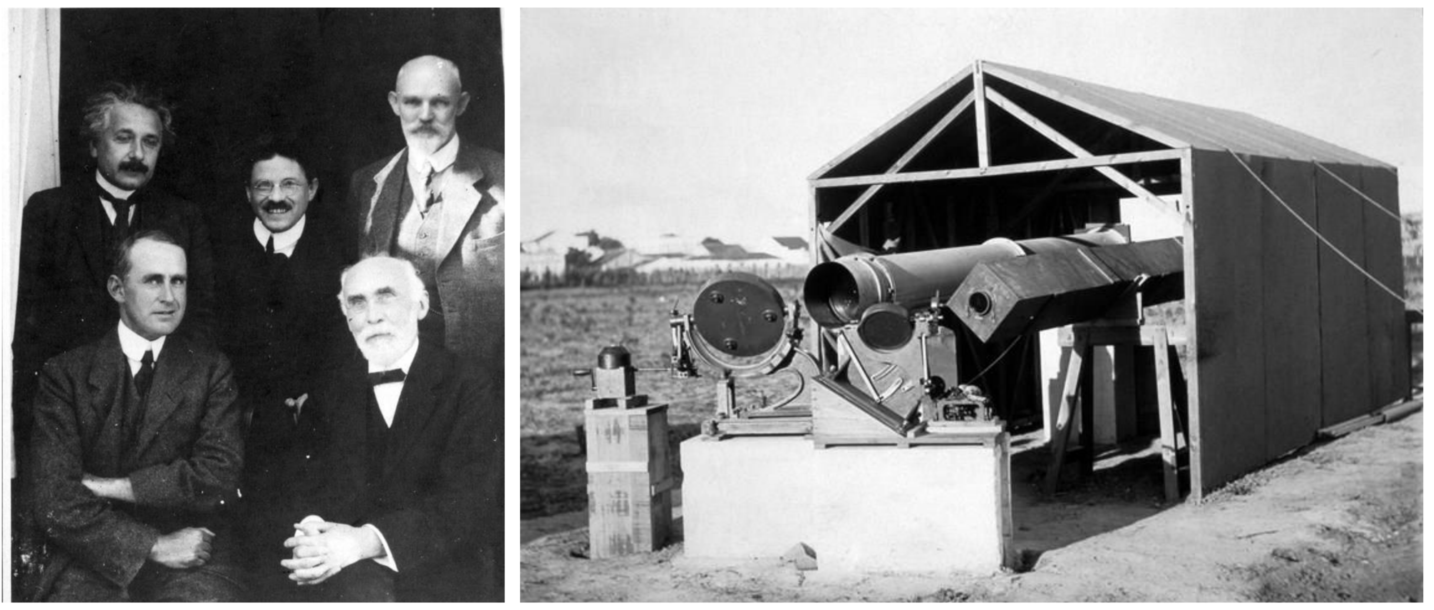

Fig. 1a (left): Einstein (top left) and Eddington (bottom left) with P. Ehrenfest (middle), W. de Sitter (top right) and H. Lorentz (bottom right) in 1923; Fig. 1b (right): equipment used by Eddington to observe the solar eclipse of 1919.

Introduction

Among the most important events in the history of science was the overthrow of Newton's theory of gravitation by Albert Einstein's theory of General Relativity. This overthrow was accomplished almost overnight as a result of observations made by the English astrophysicist Arthur Eddington and his colleagues during the total solar eclipse of May, 1919 [1-3]. To make them, they had to travel by steamship to the path of totality in Brazil and West Africa, carrying large amounts of heavy equipment such as 16-inch telescopes and photographic plates (Fig. 1). When their results were announced in November of that year, the front page of the *New York Times* read: "LIGHTS ALL ASKEW IN THE HEAVENS! … EINSTEIN THEORY TRIUMPHS!"

In Einstein's theory, gravity is not a force acting through space between massive bodies (as in Newton's theory). Rather, it is a manifestation of the *shape of space* around those bodies. The Sun's mass warps space, bending light rays from background stars so that they appear to be deflected away from the Sun as seen from Earth (Fig. 2). The effect is only visible during a total solar eclipse, when the Sun passes behind the Moon, because the stars are otherwise lost in the glare of the Sun. Space curvature actually produces only one-half of the total deflection; the other half is explained by the Equivalence Principle, which states that the effects of gravity are equivalent to those of acceleration. If you shoot a light beam across an elevator car that is accelerating upward, the beam hits the opposite wall at a lower point. This looks like a curved path to someone in the elevator. Hence, since gravitation is equivalent to acceleration, light must follow the same curved path in a gravitational field. The total deflection due to *both* effects together is

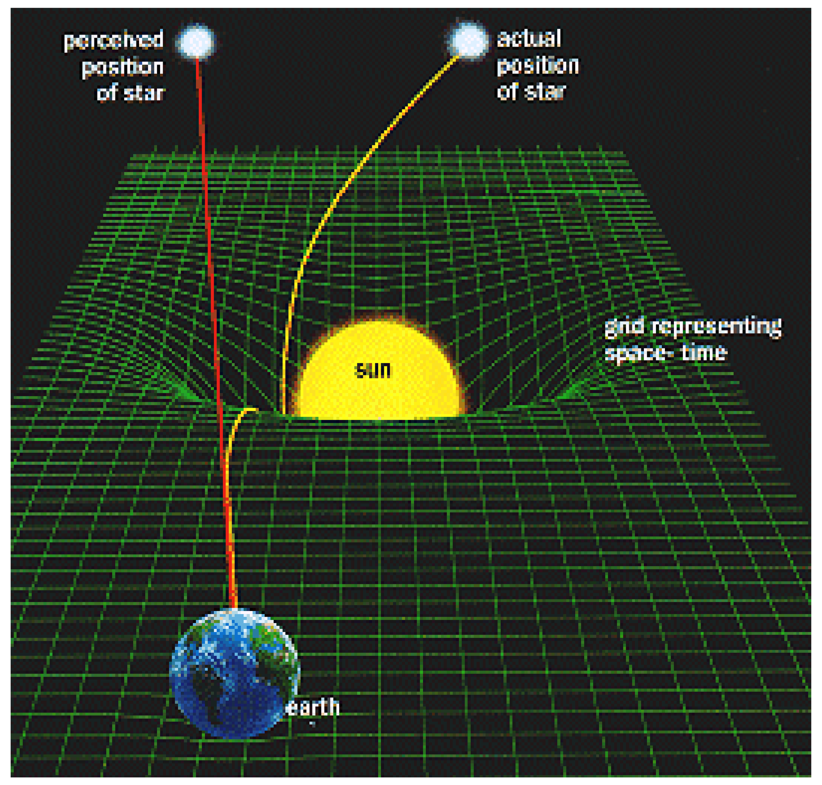

Fig. 2: Schematic depiction of light deflection due to curved space

$$\Delta\theta = \frac{4GM_\odot}{c^2 R} = \frac{1.7"}{R/R_\odot}, \quad (1)$$

where G is Newton's gravitational constant, c is the speed of light, $M_\odot$ and $R_\odot$ are the mass and radius of the Sun, R is the distance from the Sun, and we convert from radians to arcsec (") via 1 rad = 206,265".

Procedure

We had two advantages on Eddington. First, advances in optics and solid-state physics meant that we did not need large telescopes or bulky photographic plates. To test Eq. (1), we needed to be able to detect of shift of about 1" in a field of view about $1-2°$ across (i.e., several times the size of the Sun, angular diameter 0.5°). In 1919 this required the resources of the British Royal Astronomical Society, but today it is within the grasp of an ordinary digital SLR camera attached to modest refracting telescope (Fig. 3). Second, the eclipse of 2017 came to us. We chose an observing site at the closest point of approach of totality to our home institutions, an 8-hour drive away in Lexington, SC (Fig. 4).

Fig. 3: Keri McClelland with our equipment, including a Canon T3i/600D camera attached to the eyepiece of a 12 cm Sky-Watcher Pro 120ED apochromatic refracting telescope with Orion Atlas Equatorial mount and piggy-backed 8 cm short-tube Orion ST80 autoscope with a ZWO ASI120 camera (red in figure).

A second team led by B. Eney traveled to Madras, OR where they used a home-made 10-inch f/4.5 Newtonian telescope with a 25mm eye-piece and Sony Alpha A6000 camera.

A third team led by J. Mouette observed from Indian Valley, ID using a Takahashi FSQ 106 ED refractor and Sony video camera.

We also had two disadvantages. First, skies today are not as clear as they were in 1919. To mitigate the risk of failure due to bad weather or observing conditions generally, we made contact with two other teams planning to image the eclipse elsewhere along the path of totality: one led by Brian Eney in Madras, OR and the other by Jean Mouette in Indian Valley, ID. (A similar strategy was also followed by Eddington in 1919.) Second, the stars were not as favorably placed as they had been for Eddington. He was lucky that the Sun happened to be passing through a group of bright stars (the Hyades cluster) in May 1919. We ran a simulation using the free software *Stellarium* and learned that there would only be two potentially observable stars near the Sun during totality on August 21, 2017: GM Leo ("Star A") and HD 86898 ("B"). Both are 7th magnitude stars, too faint to see with the naked eye. Each would be at a distance $R/R_\odot = 1.4$, so that it would deflected by $\Delta\theta = 1.2"$ according to Eq. (1). Fortunately they would be positioned on either side of the Sun, so that their *angular separation* would increase by 2.4". It should be possible to detect this change relative to the distance between any pair of more distant reference stars lying too far from the Sun to be affected by light deflection.

We conducted two practice runs, first imaging the target stars in Leo during the evening to establish scale and resolution (in Towson, MD on May 26) and then testing our equipment during daytime conditions (in Columbia, MD on August 16). We drove to the viewing site on August 19 and 20.

Fig. 4: Viewing the eclipse in Lexington, SC. From left to right: C. Miskiewicz, K. Glazer, K. McClelland, A. Genus and J. Overduin

Results and Conclusions

Conditions in South Carolina were cloudy until moments before first contact, and we did not obtain useable images. Our colleagues in Oregon fared better but faced issues with smoke from forest fires. The best results came from our colleagues in Idaho, but even in those images the target stars are hidden in an unexpectedly bright solar corona. We are in the process of analyzing those images.

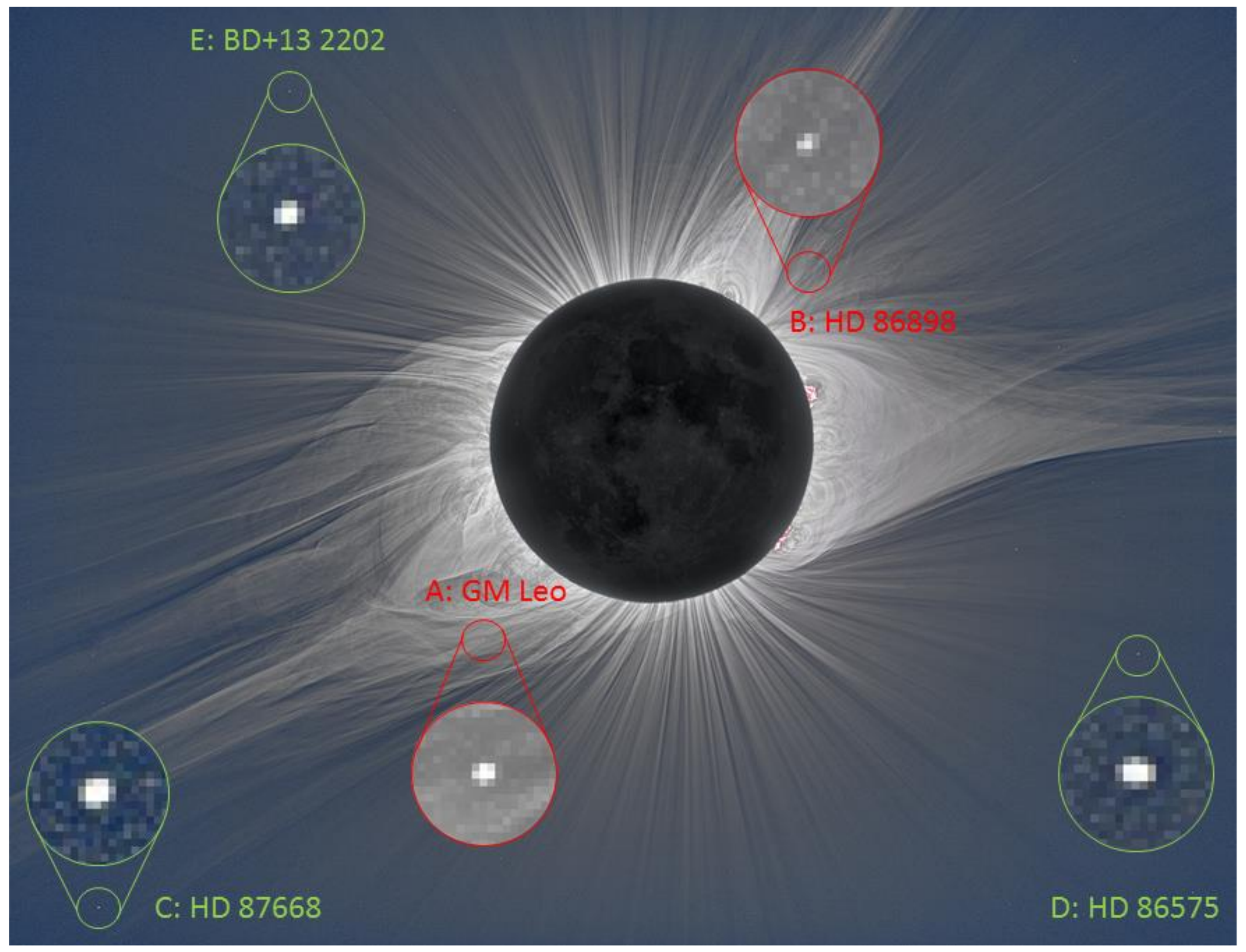

Fig. 5: Stacked composite of 161 images of the total solar eclipse as observed by from Mitchell, OR using two TS-Optics Photoline 115 mm Triplet Apochromatic refractors with Nikon D810 cameras (© 2017, Miroslav Druckmüller, Peter Aniol, Shadia Habbal, used by permission). The insets show our analysis of this image, including the target stars (A and B) and three more distant reference stars (C,D,E) lying far enough from the Sun for their images to be unaffected by light deflection.

In the meantime, we have obtained a composite of 161 images of this eclipse from another observer (Fig. 5). Both target stars are clearly visible (A,B; red insets) along with three distant reference stars: HD 87668 ("Star C"), HD 86575 ("D") and BD+13 2202 ("E"; green insets). To establish an angular distance scale, we transform from (x, y) coordinates in the image (in px) to right ascension α and declination δ in the sky (in deg) via

$$\alpha = \alpha_0 + \beta(x\cos\varphi + y\sin\varphi), \qquad \delta = \delta_0 + \beta(-x\sin\varphi + y\cos\varphi), \qquad (2)$$

where (α_0, δ_0) is the location of the image origin (in deg), β a rescaling factor (in deg/px) and φ a rotation angle. These are 4 unknowns, for which we can solve by applying Eqs. (2) to *any two* reference stars with measured positions (x_1, y_1) and (x_2, y_2) in the image and known locations (α_1, δ_1) and (α_2, δ_2) in the sky. We do this for all three pairs of reference stars (CD, DE and EC) and average the results. We then apply Eqs. (2) with the known values of $\alpha_0, \delta_0, \beta$ and φ to find (α_A, δ_A) and (α_B, δ_B). The angular separation of Stars A and B in in our image is then given by the fundamental formula of spherical trigonometry [4]:

$$\theta = \cos^{-1}[\sin\delta_A \sin\delta_B + \cos\delta_A \cos\delta_B \cos(\alpha_A - \alpha_B)] = 2957 \pm 10"\,. \quad (3)$$

By comparison the *true* angular separation between Stars A and B is $\theta_0 = 2953"$. Taking the difference, we find that Stars A and B have been deflected apart by $\Delta\theta = \theta - \theta_0 = 4" \pm 10"$, consistent with the predicted figure of 2.4". We expect this uncertainty to come down with further analysis, confirming the validity of Einstein's theory of General Relativity.

Acknowledgments

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References

[1] Dyson, F.W., Eddington, A.S. and Davidson, C., "A determination of the deflection of light by the Sun's gravitational field, from observations made at the total eclipse of May 29, 1919," *Phil. Trans. R. Soc. London* A 220 (1920) pp. 291-333

[2] Coles, P., "Einstein, Eddington and the 1919 Eclipse," in V.J. Martínez, V. Trimble and M.J. Pons-Bordería (eds) *Historical Development of Modern Cosmology* (San Francisco: ASP Conf. Proc. Vol. 252, 2001) pp. 21-41

[3] Kennefick, D., "Testing relativity from the 1919 eclipse—a question of bias," *Physics Today* 62 (2009) 27

[4] W.M. Smart, *Text-Book on Spherical Astronomy* (Cambridge University Press, 3rd ed., 1940) Sec. I.5