What are the main objectives behind your current research into dark matter halos?

My research aims to use weak galaxy-galaxy lensing to place constraints on the amount and distribution of dark matter around galaxies. My PhD student, Brandon Harrison, and I are making realistic Monte Carlo computer simulations of galaxy-galaxy lensing using galaxies from the Sloan Digital Sky Survey (SDSS). We embed each of the SDSS galaxies inside a cold dark matter halo, where the details of the halo parameters for each of the simulated galaxies are tied directly to the observed properties of the SDSS galaxies. We then place a population of distant source galaxies behind the theoretical SDSS galaxies, and lens the images of each of the source galaxies by all of the foreground theoretical SDSS galaxies.

In this way, we can make accurate predictions for the galaxy-galaxy lensing signal that should be observed in the real Universe. We then measure the resulting galaxy-galaxy lensing signal in the simulation, interpreting it in the same way that observational astronomers analyse observations of galaxy-galaxy lensing in the real Universe. Through this, we can explore the magnitude of systematic errors that will manifest in observational studies simply due to the way the signal is interpreted.

How did you begin studying dark matter and gravitational lensing?

As a graduate student, I studied the formation of dark matter halos using computer simulations. I was drawn to the topic because computer simulations are one of the only ways in which we can ‘experiment’ with the Universe. My dissertation advisor, Jens Villumsen, was visiting the California Institute of Technology (Caltech) and, through a conversation with Roger Blandford, became interested in using gravitational lensing to map the large-scale structure of the Universe. Roger and one of his students, Anne Berit Saust, had been having difficulty solving an equation that was related to gravitational lensing. One day, I went to lunch with Jens and he asked me if I would be willing to take a look at the equation. I agreed, and a few days later faxed the full solution to Roger. This initiated a collaboration between Roger, Jens, Anne and me that resulted in a landmark publication on the theory of weak lensing in relation to the large-scale structure of the Universe.

After earning my PhD, I continued to work with Roger at Caltech on aspects of weak gravitational lensing but from an observational standpoint. We placed the first upper limit on the amount of lensing by large-scale structure that exists in the Universe and published the first statistically significant detection of what has come to be known as galaxy-galaxy lensing.

Could you explain the differences between photometric and spectroscopic redshifts for galaxies?

Due to the expansion of the Universe, all galaxies outside our Local Group appear to be moving away from us, which manifests as a redshift in the spectrum. In the case of spectroscopic redshifts, a telescope and spectrograph have been used to observe the actual spectrum of galaxies. This is compared to a rest spectrum to make an accurate measurement of the galaxy’s recession velocity. In photometric redshifts, the galaxies are typically observed using four or five broad filters that allow a wide range of wavelengths of light to pass through. By comparing the brightness of the galaxy as observed through all of these filters, one can estimate its redshift. Photometric redshifts are less accurate than spectroscopic redshifts, but also require much less telescope time.

How do these measurements relate to your work?

For the purposes of lensing, it all comes down to one factor: how accurately do you need to separate your foreground objects (the lenses) from your background objects (the lensed sources)? Part of my work focuses on how accurate photometric redshifts need to be in order to make precision measurements of weak gravitational lensing.

What is your input into NASA’s Wide-Field Infrared Telescope (WFIRST) mission?

My work is potentially very important for the WFIRST mission, which has the goal of using weak lensing to measure the dark matter mass distribution with unprecedented accuracy. My current investigation centres on how well standard methods of converting the observed weak lensing shear into a measurement of surface mass density actually work. We are finding that the standard method leads to an error of ~25 per cent, which is unacceptably large in the ‘era of precision cosmology’.

Cosmological pioneer Dr Tereasa Brainerd shines a light on her work using weak gravitational lensing and details the challenges of making accurate measurements in cosmology
Curves in space

Members of Boston University’s Department of Astronomy are using a cosmological phenomenon called weak gravitational lensing to map dark matter in the Universe. Their work will provide important theoretical insights that are relevant to future space-based studies.

**DARK MATTER MAKES** up around 85 per cent of the mass of the Universe, but remains one of the greatest mysteries of astronomy. The visible material within galaxies is observed to be moving so quickly that its mass alone is insufficient to keep the galaxies bound together by gravity. The reason that the visible material can move so quickly, yet the galaxies are not torn apart, is due to the presence of dark matter. Dark matter, which gives galaxies additional mass by providing the gravity they need to stay intact – is inherently mysterious. It does not absorb, reflect or emit light, and can only be detected from its gravitational effects. However, using the phenomenon of galaxy-galaxy lensing, it is possible to determine the quantity and distribution of dark matter around galaxies.

**THE POWER TO BEND LIGHT**
According to Einstein’s theory of general relativity, mass causes space to curve. After being emitted by distant galaxies, particles of light – photons – travel along a straight path through the Universe, but under the influence of a large mass, such as another galaxy, the paths of the photons are bent. Because of the curvature that their mass causes, galaxies act as lenses, bending the paths of light emitted by distant objects. These astronomical gravitational lenses are similar to conventional glass lenses but have a variable index of refraction. Since the gravitational potential of the lens varies across the plane of the sky, gravitational lensing produces a similar effect to looking through the bottom of a wine glass, resulting in a distorted image.

Strong gravitational lenses produce highly distorted and magnified images, and multiple versions of each object. Conversely, weak lensing produces only mild distortions. Since the distortion is at most a few per cent, weak lensing cannot be detected using the image of a single lensed galaxy – it can only be detected by performing statistical averages over many galaxies.

**GALAXY-GALAXY LENSING**
Over the past 25 years, this phenomenon (weak lensing) has become a standard tool for cosmological studies. Observations of weak lensing allow cosmologists to map the amount and location of dark matter directly, and are also useful for constraining fundamental cosmological parameters independently of other methods.

Making an important mark on this field is Dr Teresa Brainerd, who pioneered understanding in the field in the 1990s. Together with her collaborators Professor Roger Blandford and Dr Ian Smail, she demonstrated the existence of galaxy-galaxy lensing in our Universe – the effect whereby distant galaxies are systematically lensed by foreground galaxies at a weak level – and she also performed the first simulations that showed it to be a multiple deflection problem. Brainerd is presently Associate Professor and Chair of the Department of Astronomy at Boston University, USA, where she is simulating galaxy-galaxy lensing in order to infer the amount of dark matter in the Universe.

**ON A MISSION**
This work is funded by the NASA Astrophysics Theory Program (ATIP), which supports theoretical investigations of astrophysical phenomena targeted by NASA astrophysics missions. Indeed, there is a tight link here, as Brainerd’s investigations are directly related to weak lensing studies that will use data obtained by NASA’s future astrophysics mission: the Wide-Field Infrared Telescope (WFIRST).

Currently the top-ranked large space mission in the New Worlds, New Horizon (NWNH) Decadal Survey of Astronomy and Astrophysics, WFIRST will obtain deep images in multiple bandpasses, and redshifts of millions of galaxies, in order to investigate the weak lensing effect known as cosmic shear. Combined, the data collected by WFIRST will represent an unprecedented weak lensing dataset, which will be used to conduct extensive studies of cosmic magnification and galaxy-galaxy lensing, as well as cosmic shear. Brainerd’s theoretical investigations will be directly relevant for interpreting these future observations.

**MATHEMATICAL DILEMMAS**
Working with PhD student Brandon Harrison, Brainerd is testing the application of a known theoretical relation between weak lensing shear and lens surface mass density. This relation states that, for a single gravitational lens, the weak lensing shear is directly related to surface mass density through a multiplicative constant.

Pinning down this relation has presented many challenges for Brainerd. “The problem with galaxy-galaxy lensing is that you have to deal with all of the multiple deflections,” she expounds. “All galaxies in the foreground are lensing all galaxies in the background, and the image of each background galaxy is affected by numerous foreground galaxies.” Adding to this complexity, the multiplicative constant assumes a different value for every single lens-source pair in the sample. Thus, in a realistic dataset, it can take on multiple values.

In order to infer surface mass density from measurements of shear, observers typically estimate the multiplicative constant using an average value taken from all of the lenses in the sample. So, when observers infer the surface mass density from observations of galaxy-galaxy lensing, they are actually computing a ratio of two mean values. However, the ratio of two means is not mathematically identical to the mean of a set of ratios – a mathematical inequality, which leads to systematic error.

**ELUCIDATING ERROR**
Although still in the throes of tackling a major mathematical problem, Brainerd and Harrison have made important progress. In the past year, Harrison has successfully constructed realistic simulations of galaxy-galaxy lensing using the Sloan Digital Sky Survey (SDSS). The simulation results clearly show that the observational method for inferring lens surface mass density leads to an underestimate, which can reach 25 per cent on small angular scales.
USING WEAK GRAVITATIONAL LENSING TO CHARACTERISE DARK MATTER HALOS

OBJECTIVE
To use weak galaxy-galaxy lensing to place constraints on the amount and distribution of dark matter around galaxies.

KEY COLLABORATORS
Brandon Harrison, PhD student, Boston University, USA

FUNDING
NASA Astrophysics Theory Program – award no. NNX13AH24G.

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INTELLIGENCE
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The space-based studies of galaxy-galaxy lensing due to be carried out with both NASA’s WFIRST and the European Space Agency Euclid missions aim to place much tighter constraints on dark matter mass distribution. In this context, a 25 per cent error simply due to technique will be unacceptable. This work therefore has important implications for space agencies, highlighting the need for a new standard for interpreting observations of galaxy-galaxy lensing.

FROM THEORY TO OBSERVATION
Looking beyond the project, Brainerd aims to make the transition from theory to observation, exploiting a recent investment from Boston University of US $10 million in a scientific partnership in a new 4 metre optical/near infrared telescope – the Discovery Channel Telescope (DCT). The DCT is owned by Lowell Observatory, a private astronomical research institution, and its construction was partially funded by Discovery Communications, Inc. “Over the next five to 10 years, I hope to use the DCT to make observations of gravitational lensing in order to map dark matter in the Universe, constrain the degree to which galaxies are intrinsically aligned with each other, and understand the evolution of galaxies in clusters,” concludes Brainerd.

SLOAN DIGITAL SKY SURVEY
SDSS provides a large spectroscopic database and an even bigger photometric database

- The size of the survey is important; the larger the sample, the more accurately the signals can be detected

SDSS enabled Brainerd and Harrison to predict the weak lensing signal under some very specific assumptions about the distribution of dark matter in the Universe – cold dark matter halos whose properties are scaled according to the observed properties of the galaxies

- The researchers are using SDSS as the basis of their computer simulations
- SDSS is the ‘real-world’ starting point for their simulations, used to ‘assign’ dark matter halos to SDSS galaxies
- Once the dark matter has been placed around each of the galaxies in the simulation, the lensing effects of their dark matter halos on a population of theoretical background galaxies are computed

Left: The dark matter surface mass density of the lens galaxies in one of Brainerd and Harrison’s simulations of galaxy-galaxy lensing, shown using a logarithmic scale. The lens galaxies have an average redshift of $z = 0.2$, corresponding to a distance of 2.2 billion light years from Earth. The scale size of the figure is 25 square degrees (equivalent to about 127 times the size of the full moon).

Right: The weak galaxy-galaxy lensing shear that occurs when a plane of source galaxies, all located at a redshift of $z = 0.4$ (corresponding to a distance of 3.7 billion light years), is lensed by the galaxies shown on the left. Again, a logarithmic scale has been used. Red regions correspond to regions of substantial amounts of weak lensing shear, and are much more ‘interconnected’ than the regions of high surface mass density of the lens galaxies.

DR TEREASA BRAINERD received her BSc (Hons) in Physics from the University of Alberta in 1987 and her PhD in Astronomy from the Ohio State University in 1992. She joined the faculty of the Department of Astronomy at Boston University in 1995, following postdoctoral research positions at the California Institute of Technology and Los Alamos National Laboratory. Prior to becoming Chair, she served as the Director of Boston University’s Institute for Astrophysical Research for six years. She has also held the positions of the Department’s Director of Undergraduate Studies, Director of Graduate Studies, and Chair of the Graduate Admissions Committee. In addition to galaxy-galaxy lensing, her research interests include the use of satellite galaxies to probe the dark matter distribution around galaxies and the use of cosmic magnification to constrain the large-scale structure of dark matter in the Universe.