The Contribution of Faint, Failed and Defunct Stars to the "Stellar" Masses of Galaxies

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Abstract. A substantial fraction the stellar mass attributed to galaxies is invisible: stars close to the hydrogen burning limit, brown dwarfs, white dwarfs, neutron stars and black holes. These constituents do, however, gravitationally micro-lens background quasars, thereby permitting measurement of the total stellar contribution to the mass surface density along the line of sight. We report the results of such a measurement using a sample of ten quadruply lensed quasars. We discuss the prospects for improving upon this measurement with a larger sample and describe efforts to find new quadruple lenses. If we invert our argument and take the stellar mass to be known, we derive a value for the fraction of the dark halo in MaCHOs (including \( \sim 20 M_\odot \) primordial black holes) of something less than 10\%, confirming the widely ignored result of Mediavilla et al (2009).

1. Introduction

Wikipedia defines a galaxy as “a gravitationally bound system of stars, stellar remnants, interstellar gas, dust, and dark matter.” Establishing the relative proportions of each is one of the great challenges of extragalactic astronomy. Hundreds of papers have been written on the stellar masses of galaxies, but the accuracy with which they can be measured is very much a matter of debate.

Nobody ever measures the stellar mass. That is not a measurable thing, it’s an inferred quantity. You measure light, OK? You can measure light in many bands but you infer stellar mass. Everybody seems to agree on certain assumptions that are completely unproven. – Carlos Frenk, 2017 May 15

The difficulties in measuring stellar masses are magisterially examined in a recent paper by Newman et al (2017) comparing stellar masses for three galaxies computed separately using stellar dynamics, gravitational macro-lensing and stellar population synthesis. Variants of each of the three approaches are considered. The principal source of uncertainty appears to be the contribution of dark matter in the first two methods and the low mass cutoff in the stellar initial mass function in the third. In a paper on a different galaxy by three of the same authors, Conroy et al (2017) say:

To illustrate the sensitivity of the total mass to the cutoff, for a single power law with \( \alpha = 2.7 \), the mass-to-light ratio is 70% higher if the cutoff is \( 0.05 M_\odot \) compared to \( 0.08 M_\odot \).

http://online.kitp.edu/galhalo-c17/panel1/rm/jwvideo.html (44:48)
Frenk is wrong to say that everyone agrees to certain assumptions. Schechter and Wambsganss (2004) describe a micro-lensing method for measuring the stellar-to-dark surface mass density in galaxies that macro-lens quasars. The technique measures the graininess of the gravitational potential, to which faint stars, brown dwarfs and stellar remnants all contribute, invisible though they might be. That approach has been refined (Schechter et al 2014) yielding a stellar surface mass density for a sample of ten lensing galaxies that is a factor of $1.23 \times e^{0.47}$ greater than that of a Salpeter IMF with a 0.10$M_\odot$ cutoff. The uncertainty is dominated by the small sample size.

In what follows we review the micro-lensing technique for measuring stellar masses and then report on efforts to increase the size of the lensing galaxy sample.

2. Stellar Masses from Micro-lensing

2.1. Flux Ratio Anomalies

Witt et al (1995) argued that gravitational micro-lensing is a “universal” phenomenon in gravitationally lensed quasars and that it was responsible for the flux ratio anomaly observed in MG0414+0534, where one of the images was (and still is today) more than a magnitude fainter than expected from the macro-model for the gravitational potential.

![Figure 1. Probability distribution for the ratio of observed to macro-model flux (expressed as a magnitude difference) at three different stellar mass fractions for the A2 image of the quadruple lens PG 1115+080. The different shapes of the distributions permit determination of the stellar mass fraction.](image)

While one might expect the amplitudes of those flux ratio anomalies to increase with increasing stellar surface mass densities, Schechter and Wambsganss (2002) showed the dependence is not monotonic. This is illustrated in figure 1, where the micro-lensing probability density distributions are shown for three different stellar mass fractions for the A2 image of PG1115+080, the first quadruply lensed quasar. The micro-lensing is less strong when all of the surface density is in stars than when only 10% is in stars.

One might also expect the flux ratio anomalies to depend upon the masses of the stars involved, but they have been shown to be extremely insensitive to the distribution of stellar masses (Schechter et al 2004), subject to the condition that the emission
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comes from regions small compared to the Einstein radii of the micro-lensing stars. To excellent approximation they depend only on the surface mass density.

To understand the micro-lensing fluctuations, one must remember that images appear wherever the light travel time from the quasar to the observer has a stationary point. In the absence of a lens, there will only be one image, a minimum of the light travel time. A galaxy with a sufficiently elliptical potential produces two minima, two saddle-points and a maximum, the last of which is almost always infinitely demagnified. The stars that lie close to each macro-image produce micro-minima and micro-saddlepoints, breaking the macro-images into micro-images (Paczynski 1986).

2.2. Twinkling Quasars

The micro-images are the gravitational analog of the speckles produced by the Earth’s atmosphere. The movement of the stars within the galaxy and of the galaxy relative to the quasar causes the speckle pattern to change, and with that the brightness of the speckles. The quasars scintillate, just as stars do.

This suggests a straightforward approach to measuring the surface mass density of the A2 image in PG1115+080. Carry out repeated photometric observations, accumulate a histogram of fluxes, and compare it with the panels in figure 1.

Unfortunately the timescale for gravitational scintillation in lensed quasars is of order ten years. As is often done in astronomy, one can substitute single epoch observations of a large number of similar objects for many observations of one object.

2.3. Estimating Stellar Surface Mass Density

One proceeds from stellar fluxes to stellar masses as follows:

1. Measure fluxes from images.
2. Measure/estimate stellar surface brightness at position of each quasar image.
3. Make an initial guess of $M/L$, the stellar mass-to-light ratio.
4. Carry out micro-lensing simulations and compute micro-lensing probability distributions based on adopted $M/L$.
5. Assign a figure-of-merit to measure consistency of fluxes and probability distributions.
6. Make a new guess of $M/L$ and iterate.

One can sidestep the problems associated with measuring surface brightness at the position of the quasar images and bringing the surface brightnesses to a common bandpass and epoch by using the stellar mass fundamental plane (Hyde and Bernardi 2009). Instead of $M/L$, the free parameter is a factor $F$ by which one multiplies an adopted stellar mass fundamental plane to obtain the best agreement with the observed fluxes.

3. Wanted: More Quadruply Lensed Quasars

The multiplicative uncertainty in the Schechter et al (2014) result, a factor of 1.6, would be reduced to a factor of roughly 1.3 if the sample size were quadrupled from ten to
forty. Given how long it took to assemble the first ten, one might be tempted to skip the remainder of this contribution. But the rate at which new quadruple lenses are being discovered has accelerated over the past 3 years with the availability of the VST-ATLAS (Shanks et al 2015), DES (Abbott et al 2016), and PanSTARRS (Chambers et al 2016) surveys.

In figure 2 we show images of eight of fifteen quadruply lensed quasars known to the author to have been discovered in the past three years. Two of the images are from VST-ATLAS, three are from DES and three are from PanSTARRS. The teams discovering these systems included Lin et al (2016), Agnello et al (2017), Berghea et al (2017), Ostrovski et al (2017), Lucey et al (2017), Anguita et al (private communication) and Schechter et al (to be published).

Figure 2. Eight quadruply lensed quasars discovered in the past 3 years. Images for the first two are taken from the VST-ATLAS survey, the next three from the DES, and the last three from PanSTARRS. The scales for the surveys are 0′′.21, 0′′.26 and 0′′.25 per pixel, respectively. The second image is in Sloan $r$, with all the rest in Sloan $i$.

There is reason to think that the acceleration of the discovery rate will continue. Until now lensed quasars have been found by first looking for quasar-colored objects and then resolving them into multiple images. This works at the brighter apparent magnitudes, where the light from the quasar images dominates that from the galaxy.

Lucey et al (2017) argue that at fainter apparent magnitudes, the light from the galaxy will dominate that from the quasar. They report the discovery of two quadruply lensed quasars that, at first, were thought to be galaxies. What singled these objects out was their differential deblending in the 2MASS and PanSTARRS catalogs. This produced astrometric offsets that called for further scrutiny. Lemon et al (2017) use differential deblending in the SDSS and GAIA catalogs, but they start with known quasars. They might equally well have started with galaxies.

4. A Challenge: The Size of Quasar Continuum Emitting Regions

While we may not be making the same “completely unproven” assumptions as other investigators measuring stellar masses, we have our own set of assumptions. In particular, we assume that the continuum emitting region producing the flux ratio anomalies is sufficiently small – much smaller than the Einstein radii of the micro-lenses – that it can be treated as a point source.

In their original paper, Schechter and Wambsganss (2004) analyzed optical fluxes and obtained inconsistent results assuming pointlike emitting regions. They were able
to reconcile those discrepancies by adopting a toy model in which 50% of the flux was pointlike and 50% of the light was very extended and not subject to micro-lensing.

Subsequent work by Pooley et al (2007), Morgan et al (2010) and Blackburne et al (2011) showed that the continuum emitting regions of bright lensed quasars were factors of 3 - 30 larger than predicted by the venerated Shakura and Sunyaev (1973) model.

Schechter et al (2014) used X-ray flux ratios in their estimate of the factor by which Salpeter mass surface densities needed to be multiplied to allay concerns about the size of the continuum emitting region. Jiménez-Vicente et al (2015) took a different tack, carrying out a joint analysis of stellar mass fraction and emitting region size. The two approaches yield consistent results, albeit with large uncertainties.

The size of the X-ray sample will continue to grow as long as the Chandra X-ray Observatory continues to operate. Unfortunately none of the currently planned X-ray missions will be able to make such measurements as they lack Chandra’s resolution.

As discussed above, newly discovered quadruply lensed quasars are likely to be less luminous than those first discovered. It is reasonable to expect their continuum emitting regions to be correspondingly smaller, mitigating the effect of their partial resolution.

5. Limits on MaCHOs, Including Primordial Black Holes

In our calculations, we implicitly assume that the dark halo component of a lens is smoothly distributed. This translates to halo particles of at most planetary mass, depending upon the poorly known sizes of quasar X-ray emitting regions.

![Figure 3](image)

Figure 3. Likelihoods for a range of fractional contributions of MaCHOs to the dark matter surface density in ten lensed quasars. Note the finite likelihood for a negative fraction, which would result if a Salpeter IMF overestimates the surface mass density.

We can invert our assumptions, and take the stellar surface mass density to be known (adopting in our case a Salpeter IMF) and instead let the factor $F$ represent the
fraction of the dark halo in Massive Compact Halo Objects (MaCHOs). The goal is exactly the same as that of the MaCHO Project (Alcock et al 2000), but we use the static micro-lensing of quasars rather than the time-variable micro-lensing of stars. A significant advantage of the present technique is that there is no upper limit to masses of the compact objects.

Mediavilla et al (2009) used static micro-lensing to place explicit limits on the fraction of halo in the form of primordial black holes, a subject reviewed by Carr et al (2016). Their argument was refined by Mediavilla et al (2017). They use optical rather than X-ray flux ratios and the overlap between the two samples is only 50%, so one might think it worth the investment of time to re-analyze the Schechter et al (2014) sample.

The investment was very small. Exactly one line of code needed to be changed. Results from that effort are shown if Figure 3. The most likely fraction of the dark halo in MaCHOs is something less than 10%, confirming the results of Mediavilla et al (2009). Carl Sagan famously said “Extraordinary claims require extraordinary evidence.” We suspect Sagan would have preferred to explain the small excess granularity in lensing galaxies as the product of a somewhat higher stellar surface mass density.

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Jeremy is unusual among astronomers in that he has always insisted on thinking things through for himself. One might have thought this was among the first requirements for a scientist. With Jeremy it is actually the case. In thinking about our past interactions I can hear his exaggerated “hmmmmmmmmm” in response to some new idea or result. I can also hear him saying “It seems to me ...” followed by a careful argument. While I won’t get to hear his “hmmmmmmmmm” when he reads this contribution, I do look forward to an email beginning “It seems to me ...”.

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