New evidence for a cosmological distribution of stellar mass primordial black holes

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ABSTRACT

In this paper we show that to explain the observed distribution of amplitudes in a large sample of quasar lightcurves, a significant contribution from microlensing is required. This implies the existence of a cosmologically distributed population of stellar mass compact bodies making up a large fraction of the dark matter. Our analysis is based on the lightcurves of a sample of over 1000 quasars, photometrically monitored over a period of 26 years. The intrinsic variations in quasar luminosity are derived from luminous quasars where the quasar accretion disc is too large to be microlensed by stellar mass bodies, and then synthetic lightcurves for the whole sample are constructed with the same statistical properties. We then run microlensing simulations for each quasar with convergence in compact bodies appropriate to the quasar redshift assuming a ΛCDM cosmology. The synthetic lightcurve is then superimposed on the amplification pattern to incorporate the effects of microlensing. The distribution of the resulting amplitudes can then be compared with observation, giving a very close match. This procedure does not involve optimising parameters or fitting to the data, as all inputs such as lens mass and quasar disc size come from independent observations in the literature. The overall conclusion of the paper is that to account for the distribution of quasar lightcurve amplitudes it is necessary to include the microlensing effects of a cosmologically distributed population of stellar mass compact bodies, most plausibly identified as stellar mass primordial black holes.

Key words: quasars: general – gravitational lensing: micro – dark matter

1 INTRODUCTION

The idea that dark matter in the form of compact bodies might be detected by the microlensing of quasars was first suggested in a classic paper by Press & Gunn (1973). They pointed out that if the Universe contains a roughly critical density of compact bodies, then the probability that a distant point light source such as a quasar will be gravitationally lensed is very high. For a lens mass of ~ 1M\(_{\odot}\) the distant source will be split into two or more images with a separation of the order of 10^{-6} arcsec, resulting in a change of observed integrated brightness. In the event that the lenses are of order a solar mass, the brightness will be observed to change on a timescale of a few years as the lens passes across the source as a result of their combined random motions. Canizares (1982) developed this idea with particular reference to lenses of around a solar mass, and concluded on the basis of datasets available at the time that such objects were unlikely to be sufficiently numerous to close the Universe.

The idea that dark matter in the form of compact bodies might be detected from the microlensing of quasars was investigated in more detail by Hawkins (1993), with the conclusion that a number of features in the statistics of observed quasar lightcurves were consistent with the predictions of microlensing, but were hard to explain in the context of models of intrinsic variation current at the time. Further evidence favouring the microlensing of quasars came from features observed in quasar lightcurves which were best explained as caustic crossing events resulting from a large optical depth of microlenses (Hawkins 1998). In the ensuing years a number of investigations in varied contexts suggested the presence of dark matter in the form of compact bodies, and are summarised in the form of a case for primordial black holes as dark matter by Hawkins (2011).

An alternative approach proposed by Schneider (1993) to set limits on any population of compact bodies involved simulating amplitude fluctuations due to microlensing for varying combinations of lens mass and cosmological density. The amplitude distribution for each model was then compared with the observed amplitudes for a sample of 117 quasar lightcurves covering a period of 10 years (Hawkins & Véron 1993). The results of this study were that in almost all cases the expected microlensing amplitudes from the simulations were greater than those observed in the quasar sample. However, Schneider (1993) pointed out that there were a number of assumptions associated with these results. These include the multiplication assumption for calculating the amplification produced by adjacent lenses, the distribution of tangential velocities for the lens relative to the source and observer, and the size of the quasar disc. Of these, the multiplication assumption turned out to provide sufficient accuracy for Schneider’s purposes, the tangential velocities affect the estimation of the lens masses which was not central to Schneider’s line of argument, but the most significant has turned out to be the source radius, which Schneider set to 10^{15} cm or 0.4 lt-day. Recent measures of the size of quasar accretion discs from microlensing (Jiménez-Vicente et al.
and reverberation mapping (Mudd et al. 2018) imply values an order of magnitude larger than this, with a characteristic radius of around 4 lt-day. This has a major impact on the results of Schneider (1993).

The approach pioneered by Schneider (1993) to put bounds on the cosmological density of compact objects was adapted by Zackrisson & Bergvall (2003) to incorporate the \( \Lambda \)CDM cosmology using the same sample of quasar lightcurves (Hawkins & Véron 1993), and to investigate the effects of source size and tangential velocity on microlensing probabilities. The assumption of a nonzero value for the cosmological constant \( \Lambda \) is well-known to increase the optical depth to microlensing \( \tau \) for a given cosmological density \( \Omega_L \) of compact bodies, or lenses. This is well illustrated by Fukugita et al. (1990) for both point masses and isothermal spheres, and has the effect of tightening the limits on the cosmological density of lenses \( \Omega_L \), as the probability of microlensing increases. In fact, Fukugita et al. (1990) suggest that the analysis of the distribution of lenses as a function of redshift could be a way of putting limits on the value of the cosmological constant, but Zackrisson & Bergvall (2003) opted to use a concordance value for \( \Lambda \), thus eliminating a potential free parameter in setting limits on \( \Omega_L \). Zackrisson & Bergvall (2003) also investigate the effect of changing the assumptions on the transverse velocity distribution of the lenses, which has the effect of changing the length of the simulated lightcurves relative to the Einstein radius for given lens masses, and find that constraints on the upper limit to \( \Omega_L \) are only weakly affected by such changes. The most important result presented by Zackrisson & Bergvall (2003) concerns the effect of source size on limits to \( \Omega_L \). They conclude that increasing the source radius \( R_s \) to 4 lt-day results in no meaningful constraint on the value of \( \Omega_L \). This can be seen in the context of current measures of the accretion disc size for quasars of between 4 and 8 lt-day (Jiménez-Vicente et al. 2015; Mudd et al. 2018).

Given the difficulty of distinguishing between the intrinsic variability of quasars and variations caused by microlensing, the emphasis for detecting dark matter in the form of compact bodies switched to the halo of the Milky Way. The idea here was that if there were a significant population of stellar mass compact bodies making up the dark matter component of the Milky Way halo, then by monitoring several million stars in the Magellanic Clouds one should occasionally observe a microlensing event (Paczyński 1986). This would be caused by a stellar mass body crossing the line of sight to one of the Magellanic Cloud stars and acting as a gravitational lens, amplifying the starlight in a characteristic way as a function of time. By analyzing the statistics of the observed events, limits can then be put on the population of compact bodies in the Milky Way halo, and hence on their fractional contribution to the halo dark matter. In order to put this idea to the test, the MACHO collaboration (Alcock et al. 2000) undertook a large scale photometric monitoring programme in which they observed several million Magellanic Cloud stars in two passbands on every available night for 6 years. The final results rested on their assumption of a high mass Milky Way halo, and the reliability of their estimate of efficiency in detecting microlensing events. The widely quoted conclusion of this experiment was to rule out a dark matter halo composed of solar mass compact bodies. However, the 15 microlensing events which they did observe were far more than expected on the basis of the stellar population of the Milky Way halo (Alcock et al. 2000). Such a large population of halo stars would have been readily detected in existing surveys for high velocity, low metallicity stars. A detailed analysis of the contribution of stars from the Milky Way and LMC to the optical depth to microlensing is given by Alcock et al. (2000). This includes the spheroid and disc populations of the Milky Way, and the halo population of the LMC. They find the total optical depth attributable to stellar microlensing to be of order \( \tau_s \sim 1 \times 10^{-8} \) compared with the observed value of \( \tau \sim 1.2 \times 10^{-7} \). The identity of these lenses has yet to be determined, but they may indicate a less simplistic solution to the nature of halo dark matter. Other groups carried out similar experiments, including EROS (Tisserand et al. 2007) and OGLE (Wyrzykowski et al. 2011), which tended to tighten the constraints published by Alcock et al. (2000), although all groups used the same halo model for their analysis. After some 15 years, these results have now been widely challenged. Hawkins (2015) pointed out that more recent observations imply a light halo for the Milky Way, which reduces the expected microlensing rate such that it is compatible with a dark matter halo composed of stellar mass compact bodies. The paper also highlights a number of inconsistencies in the way the detection efficiency was calculated. Other concerns have been raised by Green (2017) who points out the sensitivity of the result to the assumed mass function of the lenses, and Calcino et al. (2018) who show that...
for a clumpy mass distribution in the halo, microlensing constraints will become weaker especially in the stellar mass range.

More recently, a new window has been opened up for the detection of black holes in the Galaxy (Wyrzykowski & Mandel 2020). The idea here is to look in the Galactic bulge for “dark” lensing events, where the contribution of light from the lens is negligible. This approach has already produced some intriguing results, with a number of new black hole and neutron star candidates. Of particular interest is the failure to find useful evidence for a mass gap between neutron stars with masses of up to $2M_\odot$ and black holes with masses over $5M_\odot$. This mass gap has been detected in the mass distribution of X-ray binaries (Özel et al. 2010), and there seems to be no compelling reason why it is not seen in the Galactic bulge observations. There are several possible explanations, including ‘natal kicks’ where the black hole receives a boost to its tangential velocity at formation, giving rise to misleading mass estimates. An intriguing possibility suggested by Wyrzykowski & Mandel (2020) is that the gap is filled by primordial black holes, which would not be subject to the constraints from X-ray observations as they would not be found in X-ray binaries.

The challenge to constraints on compact bodies in the Milky Way halo has re-opened the possibility of detecting a population of compact bodies on a cosmological scale that make up part or all of the dark matter. A promising place to look for such a population is in gravitational lens systems where a quasar is split into multiple images by a massive galaxy or cluster. Although intrinsic variations in the quasar will show up in the lightcurves of all the images, it is well known that the quasar images also vary independently. This is generally accepted to be the result of microlensing along the line of sight to the quasar. Until recently, it has been believed that the microlenses are stars in the halos of the lensing galaxy or cluster (Mediavilla et al. 2009; Pooley et al. 2012), but recent work (Hawkins 2020a,b) based on direct measures of starlight along the line of sight to the quasar images has shown that the stellar populations in the galaxy or cluster halos are too sparse to account for the observed microlensing. The compact bodies comprising the lenses must make up a substantial proportion of the dark matter, and are tentatively identified as primordial black holes.

In this paper we build on the result of Schneider (1993) to determine whether a cosmological distribution of compact bodies betray their presence in the lightcurves of quasars which are not part of gravitational lens systems. It is important to point out that as stars make up only around 1% of the critical density (Fukugita et al. 1998), this implies an optical depth to microlensing due to stars of $\tau_s \sim 0.01$. This means that if microlensing is detected at any significant level it must be associated with a component of dark matter made up of compact objects. We first repeat Schneider’s experiment in the context of the $\Lambda$CDM cosmology with a sample of over 1000 quasars, and confirm the result of Zackrisson & Bergvall (2003) that if modern estimates of quasar accretion disc size are used, then the range of amplitudes observed in quasar lightcurves is consistent with microlensing simulations. We then derive the distribution of intrinsic amplitudes of variation by using as a template the lightcurves of luminous quasars where the size of the accretion disc is too large to be significantly microlensed by stellar mass bodies. Combining this with the distribution of amplitudes from microlensing simulations, we compare the results with the observed distribution of amplitudes, and find that the two distributions match each other closely. None of the parameters used in the modelling such as the quasar disc size or lens mass are optimized or varied to fit the data, but come from independent and unrelated measurements.

2 OBSERVATIONS

The sample of lightcurves used by Schneider (1993) and Zackrisson & Bergvall (2003) covered 10 years and contained only 117 members (Hawkins & Véron 1993), which severely limited any investigation of statistical trends in redshift or luminosity. Since this early work the sample of lightcurves has been greatly enlarged, and now contains data for 1033 quasars covering 26 years in the $B_J$ and 23 years in the $R$ band. The data form part of a long term monitoring programme of the ESO/SERC field 287 with the UK 1.2m Schmidt telescope at Siding Springs Observatory in Australia from 1977 to 2002. The plates were measured by the SuperCOSMOS measuring machine at the Royal Observatory Edinburgh (Hambly et al. 2001) to give a range of parameters, including instrumental magnitude, for each detected image. These magnitudes were then calibrated with deep CCD photometric sequences to give true magnitudes for each image. For most years, 3 or 4 observations were available, giving a mean magnitude for each year with an error of ~ 0.04 mag. This procedure is described in detail in Hawkins (1986, 2003) and references therein. Examples of quasar lightcurves from the survey are illustrated in Hawkins (2003), which should give a feel for the quality of the data. In Fig. 1 we show plots of amplitude in the $B_J$ passband versus redshift and luminosity for the 1033 quasars in the sample. There is no obvious trend of amplitude with redshift, but a clear decrease in amplitude with increasing luminosity. This trend has been seen in many studies (Hawkins 2000; Vanden Berk et al. 2004 and references therein), but the explanation for it has remained unclear.

3 MICROLENSING SIMULATIONS

The measure of variability used by Schneider (1993) was the amplitude of the lightcurve. Other measures of variability such as rms variation are not as well suited to analysing microlensing lightcurves, which are typically characterized by sharp amplification events associated with caustic crossings. The purpose of Schneider’s work was to see if these large amplitude events were observed in quasar lightcurves, as a means of putting limits on any cosmological distribution of compact bodies. In order to replicate the results of Schneider (1993) with the new large sample of quasar lightcurves we repeated his microlensing simulations, but taking advantage of more recent knowledge of cosmological parameters. The simulations assume a $\Lambda$CDM cosmology with a set of cosmological parameters reflecting tensions in current measurements. For this purpose we adopt the results of Luković et al. (2016) who use a joint analysis of the JLA+OHD+BAO datasets (see Luković et al. 2016 for detailed references) to derive a consistent set of cosmological parameters. In particular, they find $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.350$ for the Hubble constant and mass fraction respectively. For the baryon density we use the results of Mossa et al. (2020), based on Big Bang nucleosynthesis, giving a baryon fraction $\Omega_B = 0.048$. Combining this with $\Omega_m$ we obtain a value of $\Omega_k = 0.302$ for the cosmological density of dark matter in the form of lenses.

Assuming this cosmology, the convergence $\kappa_s$ was calculated out to the redshift of each quasar in turn, using the equations of Fukugita et al. (1992). The software of Wambsganss (1999) was then used to simulate an amplification pattern with this value of $\kappa_s$. The next step was to superimpose a track in random position and orientation onto the simulation of the length of the quasar lightcurve, using the conventionally assumed value for the transverse velocity across the line of sight of 600 km sec$^{-1}$ (Kayser et al. 1986). This required specifying the mass of the lenses, as the Einstein radius $R_E$ provides
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Figure 2. Microlensing magnification patterns for a population of 0.3 $M_\odot$ bodies. The frames have a side length of 16 Einstein radii in the source plane, and assume a source redshift $z = 2.5$ implying a total convergence $\kappa_s = 0.266$, and a most likely lens redshift $z = 0.82$ in a $\Lambda$CDM Universe with $\Omega_L = 0.3$. In the left hand panel a point source is assumed, and the right hand panel is for a source of half-light radius 4 lt-day. Yellow lines indicate tracks across the amplification pattern corresponding to 26 years, the length of the lightcurves from the quasar monitoring programme. A net transverse velocity of 600 km sec$^{-1}$ is assumed, and the position and orientation of the track is random.

Figure 3. Lightcurves corresponding to the yellow tracks in Fig. 2. The red curve assumes a point source, and the green curve is for a source of half-light radius 4 lt-day, as for the left and right hand panels of Fig. 2 respectively.

Fig. 4 shows the result of repeating the experiment illustrated in Figure 6 of Schneider (1993) with our new sample of quasar lightcurves. To summarize, for each quasar the value of $\kappa_s$ was calculated at the redshift of the quasar for the $\Lambda$CDM cosmology of Luković et al. (2016) with $\Omega_L = 0.3$. Microlensing simulations were then run using this value of $\kappa_s$ for lens masses of $1.0M_\odot$ and $0.3M_\odot$, as illustrated in Fig. 2, and a track corresponding to the length of the observed lightcurve superimposed as described above. The simulated microlensing amplitude for each quasar was then measured from its lightcurve. In Fig. 4 the normalised cumulative histogram of amplitudes from the quasar sample is shown as a black line in both panels. The coloured lines show the cumulative probability that a source varies by more than $\Delta m$ magnitudes from cumulative histograms of
amplitudes from the microlensing simulations. The red line assumes a point source, and the blue and green lines are for sources with radius 4 and 8 lt-day respectively. The choice of these accretion disc sizes is motivated by the recent work of Jiménez-Vicente et al. (2015) and Mudd et al. (2018). It can be seen from both panels in Fig. 4 that for a point source the predicted number of large amplification microlensing events far exceeds those observed, but we also find that for realistic source sizes of 4 and 8 lt-day the largest predicted amplitudes are consistent with the observations. This is in agreement with the results of Zackrisson & Bergvall (2003).

The other notable feature of Fig. 4 is that microlensing only appears to account for part of the total variability of the quasars. This is not unexpected as intrinsic variations are a well established feature of AGN activity. In the next Section we establish a procedure for combining the varying luminosity of the quasars with the amplification due to microlensing.

4 INTRINSIC QUASAR VARIABILITY

Distinguishing between intrinsic variations in quasar luminosity and the effect of amplification by microlensing has proved to be a serious obstacle to attempts to identify a population of compact bodies acting as microlenses on a cosmological scale (Hawkins 1996). For the quasar images in gravitational lens systems this difficulty can be readily overcome and microlensing amplifications identified (Hawkins 2020a,b), but in this paper we are concerned with identifying microlensing amplifications in the general cosmological population of quasars. In order to characterise the properties of the intrinsic variations of quasars we must look for a regime where the variations are not significantly affected by microlensing. The right hand panel of Fig. 2 and the green curve in Fig. 3 suggest that the variations due to microlensing of quasars with large accretion discs will be small.

In Fig. 5 we show the relationship between quasar disc size as determined from reverberation mapping (Mudd et al. 2018) and absolute magnitude $M_B$. Also shown is the best fit straight line with slope 0.5 tracing the expected relation between $\log(R_\ast)$ and $M_B$ for a constant surface brightness disc. This relation suggests that for quasars with $M_B < -25$ the size of the accretion disc $R_\ast \gtrsim 6$ lt-day, rising to over 200 lt-day for the most luminous quasars, and thus it may be concluded from Fig. 3 that for such luminous objects microlensing will make a negligible contribution to any variability. On this basis we shall use the amplitude distribution of luminous quasars ($M_B < -25$) as a template for quasar intrinsic variation. The black histogram in Fig. 6 shows the amplitude distribution for quasars in the Field 287 sample with $M_B < -25$, and is well fitted by a lognormal distribution

$$f(x) = \frac{e^{-(\ln(x-\theta)-\mu)^2/(2\sigma^2)}}{(x-\theta)\sigma \sqrt{2\pi}}$$

shown as a continuous blue line in Fig. 6. Also shown in Fig. 6 as a red histogram is the lognormal function $f(x)$ rebinned for comparison with the data. The best fit parameters are $\sigma = 0.20$, $\theta = -0.36$ and $\mu = 0$, giving an adequate fit with $\chi^2 = 3.39$ and 7 degrees of freedom.

In Fig. 7, the black histogram shows the amplitude distribution for the full Field 287 quasar sample, with no restriction on luminosity. The continuous blue curve shows a lognormal distribution with the same best fit parameters from Fig. 6, but normalised to the 1033 quasars in the full Field 287 sample. It will be seen that there is a considerable excess of large amplitude variations in the histogram of observed amplitudes which we tentatively identify as the result of microlensing amplification by a population of compact bodies along the line of sight to the quasars. To test this hypothesis, we combine intrinsic variations with microlensing amplification to give a distribution of amplitudes for comparison with observations. This procedure is described in detail in the following Section 5.

5 QUASAR LIGHTCURE MODELS

In order to model the intrinsic variations of the quasar sample we first allocate to each quasar in turn an amplitude chosen at random from the 1033 amplitudes in the normalised lognormal distribution illustrated by the blue line in Fig. 7. This ensures that the amplitudes of the intrinsic variations accurately follow a lognormal distribution function with parameters from the fit to the data in Fig. 6. We then
construct synthetic lightcurves normalised to the allocated amplitude from a power law spectrum (Hawkins 2007), assuming random phases. The idea behind creating a lightcurve in this way is to be able to model the effect of amplification by microlensing on the intrinsic brightness changes of the quasar as it traverses the caustic pattern associated with a cosmological distribution of compact bodies comprising the dark matter.

To model the effect of microlensing on these lightcurves of intrinsic variations, the procedure described in Section 3 was used to simulate a lightcurve for each quasar at the corresponding redshift, assuming a characteristic mass for the lenses of $0.3M_\odot$. The amplification at each epoch of the microlensing lightcurve was then applied to the corresponding point of the lightcurve of intrinsic variations to model the total change in brightness of the quasar. The amplitude of this combined lightcurve was then measured to give a statistical estimate of the observed quasar amplitude in the Field 287 sample. The green histogram in the left hand panel of Fig. 7 shows the simulated distribution of amplitudes assuming a quasar disc half-light radius $R_s = 4$ lt.-day.

The green histogram of simulated amplitudes in the left hand panel of Fig. 7 closely follows the histogram of observed amplitudes in black. It is important to point out that the simulations are not fitted to the data by optimizing any free parameters, but rest on three assumptions, independently supported by observation. The first is the choice of $0.3M_\odot$ for the characteristic lens mass. This choice is motivated by the results of the MACHO collaboration (Alcock et al. 2000), discussed in Section 1, who detected a large unidentified population of compact bodies of around $0.3M_\odot$ in the Galactic halo, and which are seen as plausible dark matter candidates. The second assumption is that the photometric variations of luminous quasars are not significantly affected by microlensing amplifications due to the large size of the accretion disc, and thus provide a good template for intrinsic variability. The third assumption is the size of the quasar accretion disc. In the first instance we assume $R_s = 4$ lt.-day, based on microlensing (Jiménez-Vicente et al. 2015) and reverberation mapping (Mudd et al. 2018) measures, and the green histogram in the left hand panel of Fig. 7 is based on this assumption. An alternative approach is to assume that the surface brightness of a quasar disc is constant, and hence the disc radius $R_s$ scales with absolute magnitude as suggested by Fig. 5. The green histogram in the right hand panel of Fig. 7 is based on this assumption, and it is interesting to note that the overall shape is little changed.

We are now in a position to repeat the cosmological test introduced by Schneider (1993) using a much larger sample of quasar lightcurves, spanning a much longer time period. Rather than assuming a constant quasar luminosity, we have now incorporated intrinsic changes in quasar luminosity based on photometric variations in the most luminous quasars where the size of the accretion disc makes microlensing amplification negligible. In Fig. 8 we show an updated version of Schneider’s cumulative probability plots where intrinsic variations are amplified by microlensing from a cosmological population of stellar mass lenses with a dark matter distribution. The combination of intrinsic and microlensing variations provides a good match to the observations, and we discuss the implications of this in the following Section.

6 DISCUSSION

The investigation behind this paper was prompted by the detection of a large population of compact solar mass bodies from microlensing observations in two separate environments. In the first case (Alcock et al. 2000) the lenses were located in the dark halo of the Milky Way, and in the second case the lenses were observed in the halos of distant massive galaxies and a galaxy cluster (Hawkins 2020a,b). These projects are briefly described in Section 1. An important aspect of both these results was that the population of stellar mass compact bodies required to account for the observed microlensing was not consistent with any plausible population of stars. In the case of the Milky Way, inventories of the stellar populations in the spheroid and disc have been painstakingly built up over many decades from direct star counts, and from kinematic measures from spectroscopy and proper motions (Robin & Crézé 1986; Gilmore et al. 1989). These data have been supplemented by photometric and spectrometric abundance measurements to give an accurate overall map of the distribution of stellar populations in the Milky Way, with no room for a large new population of stellar microlenses. Early work on stellar
Figure 7. Histogram of amplitudes in the $B_J$ passband for the field 287 sample of quasars (black line). The blue line is the best fit lognormal distribution from Fig. 6, normalised for the 1033 quasars in the full sample. The green histogram shows the effect of amplification by microlensing based on the redshift of each of the sample members. In the left hand panel a half-light radius of 4 lt-day is assumed for the quasar accretion disc, and in the right hand panel the size of the accretion disc is assumed to scale with luminosity, as illustrated in Fig. 5.

Figure 8. Cumulative probability $P(\Delta m)$ that a source varies by more than $\Delta m$ magnitudes for the sample of 1033 quasars from the Field 287 survey for lens mass $0.3M_\odot$. The black curve represents the data, and the red curve shows the cumulative probability for a combination of lognormal intrinsic variation combined with microlensing amplification assuming a quasar disc radius $R_d = 4$ lt-day.

Figure 9. Amplitude as a function of luminosity for the 42 low redshift quasars in the Palomar-Green survey from Giveon et al. (1999).

populations of other galaxy types (Van den Bergh, 1975) is consistent with this picture, and the extensive work done since then on the structure of galaxies has found no evidence for such unexpected populations of stars.

The second environment where a large population of solar mass compact bodies have been detected is in gravitational lens systems where a massive galaxy is seen to split a quasar into two or four separate images. It is well established that intrinsic variations in the quasar are seen in the individual images, separated by a small time difference reflecting the time for the quasar light to reach each image. More importantly for our purposes, the individual quasar images are also seen to vary independently. This is widely recognised as the result of microlensing, as the the light from the quasar follows different trajectories to each image, and hence encounters different

amplification patterns from any distribution of compact bodies along the light path. The timescale of the microlensing events implies the lenses are around a stellar mass, and one might conclude from these observations that this is evidence for a cosmologically distributed population of stellar mass compact bodies. Given the ubiquity of the microlensing amplifications these compact bodies would make up a large fraction of the dark matter. There is however an important caveat with this conclusion. By its very nature, in a gravitational lens system a massive galaxy will lie along the line of sight to the quasar, with the possibility that the quasar images will lie close enough to the outskirts of the lensing galaxy for the galactic stars to act as microlenses. This possibility has been examined in detail for a small sample of gravitational lens systems where the microlensed quasar images appear to lie well clear of the stellar population of the lensing galaxies (Hawkins 2020a). Surface brightness measures from from Hubble Space Telescope frames in the infrared were converted to surface mass density, and hence optical depth to microlensing $\tau$ to measure the probability both analytically and from computer
simulations of stellar microlensing amplification. The results showed that the probability that the observed microlensing could be caused by stars was of the order of $10^{-4}$. A similar analysis was carried out for the cluster lens SDSS J2004+4112 where the microlensed images lie some 60 kpc from the cluster centre, and the probability of microlensing by stars again appears to be negligibly small (Hawkins 2020a).

On the basis of these constraints on microlensing by stars, the population of compact bodies making up the microlenses were identified as a component of the dark matter, most plausibly in the form of stellar mass primordial black holes (Hawkins 2020a). Given the detection of such a population of compact bodies in the halo of the Milky Way and more distant galaxies, it has been the purpose of this paper to look for evidence of their presence in the form of a cosmological distribution, tracing out the dark matter.

As a starting point for the investigation we have taken the cosmological test proposed by Schneider (1993) to put limits on the extent to which compact bodies can make up a component of the dark matter. Using a sample of quasar lightcurves a factor of 10 larger than that available to Schneider, and covering a timespan increased from 10 to 26 years, we repeated his simulations in the context of the ΛCDM cosmology. The results illustrated in Fig. 4 broadly support Schneider’s claim that for a point source the predicted large amplitude microlensing events are not seen in the observations. However, in line with the results of Zackrisson & Bergvall (2003) we find that for a quasar disc radius $R_s \gtrsim 4$ lt-day there is no such conflict between microlensing simulations and observations.

The next step in the programme was to model the intrinsic variations of the quasars. To do this we made use of the relation between quasar disc radius $R_s$ and luminosity from Mudd et al. (2018) as illustrated in Fig. 5, to identify quasars with sufficiently large accretion disc that microlensing amplifications would be negligibly small. This was achieved by adopting a limit of $M_B < -25$, to create a sample of luminous quasars with implied disc radii $R_s$ ranging from 6 to over 200 lt-day. The lightcurves in Fig. 3 give an idea of the extent to which microlensing amplitudes are reduced as $R_s$ increases. On this basis the observed distribution of lightcurve amplitudes is a measure of intrinsic variation, and is well-fitted by a lognormal distribution. Combining these intrinsic variations with microlensing amplifications gives an excellent match to the observed amplitude distribution, as illustrated in Fig. 7. Finally, reploting these data as a cumulative distribution as for the cosmological test proposed by Schneider (1993) results in a distribution of amplitudes very close to the observations.

Apart from the adoption of the ΛCDM cosmology which is not controversial in cosmological studies, this final result rests on the three assumptions outlined in Section 5. The unidentified population of compact bodies detected by Alcock et al. (2000) were found to have a characteristic mass of around $0.3M_\odot$, which is the same as the mass used to account for the observed microlensing in galaxy halos (Mediavilla et al. 2009; Pooley et al. 2012) and clusters (Hawkins 2020b). It is also close to the preferred mass of $0.7M_\odot$ from theoretical studies of primordial black hole formation during the QCD phase transition (Byrnes et al. 2018; Carr et al. 2021).

The reduction in microlensing amplitude with increasing source size was thoroughly discussed and modelled some time ago by Rees & Stabell (1991), and is again illustrated here in Fig. 3. It is clear from Fig. 5 that quasars with luminosity $M_B \lesssim -25$ already have an accretion disc radius $R_s \gtrsim 6$ lt-day, half as large again as the assumed value for $R_s$ in Fig. 3 which already shows much reduced variation due to microlensing. On this basis we have assumed that the variations in quasars with $M_B \lesssim -25$ are intrinsic variations in quasar luminosity.

The third assumption that the size of the quasar accretion disc radius $R_s = 4$ lt-day is based on extensive work on the subject by a number of authors (Jiménex-Vicente et al. 2012, 2015; Mosquera et al. 2013; Mudd et al. 2018), and results in a very good fit to the data as may be seen in the left hand panel of Fig. 7. The alternative assumption of a constant mass-to-light ratio for the quasar disc produces a few outliers from low luminosity quasars, but otherwise gives a similar fit. In Fig. 8 the data are shown re-plotted as cumulative histograms in the form originally proposed by Schneider (1993). The combined model including intrinsic variations combined with microlensing amplification from a cosmological distribution of $0.3M_\odot$ compact bodies making up the dark matter closely reproduces the observations, without the need for parameter optimization. There are a number of strong constraints on the identity of such dark matter compact bodies which have been discussed in detail by Hawkins (2020a), with the conclusion that the only plausible candidates are primordial black holes.

The idea that microlensing amplification contributes to the observed distribution of quasar amplitudes provides a possible solution to the long standing question of why the amplitude of quasar variation appears to decline with luminosity, contrary to theoretical expectations (King et al. 2004). Luminous quasars with larger accretion discs will become progressively less affected by microlensing amplifications, thus producing the observed trend. Some evidence in support of this can be seen by considering the optical variability of the well known Palomar-Green sample of nearby bright quasars (Giveon et al. 1999). Fig. 9 shows a plot of amplitude over a 7 year period versus absolute magnitude $M_B$ for the 42 quasars. The plot shows no correlation between amplitude luminosity, with a correlation coefficient of 0.16. The maximum redshift of these quasars is $z = 0.371$, corresponding to an optical depth to microlensing $\tau = 0.010$, or a probability of significant microlensing amplification of less than 1%. This provides a consistent explanation for the difference between the Palomar-Green lack of correlation of amplitude with luminosity, and the well-known anti-correlation seen in other samples.

7 CONCLUSIONS

The stimulus for this paper has been the detection of a population of compact bodies in the Milky Way halo, and the halos of more distant galaxies and galaxy clusters. These bodies are most plausibly identified as primordial black holes, and would make up a large component, and possibly all, of the dark matter. In this case these bodies should betray their presence by the microlensing amplification of quasar lightcurves in the general field. The starting point of the investigation was early work setting limits on a population of stellar mass bodies by considering the absence of very large amplitude fluctuations in quasar lightcurves. Later work showed that the adoption of a more realistic size for the quasar accretion disc removed the expectation of large amplitude quasar fluctuations in contradiction with observations. However, the question still remained as to the extent to which quasar variations in brightness were amplified by compact bodies.

This paper is based on a large sample of over 1000 quasar light curves, monitored over a period of 26 years and covering a wide range of luminosities and redshifts. The amplitude distribution of luminous quasars, where the size of the accretion disc is too large to permit microlensing of stellar mass bodies, was used as a template for the intrinsic variations in quasar luminosity for the whole sample. It was
found that to provide a match to the data a significant contribution from microlensing amplification was required, and so the resulting synthetic lightcurves were superimposed on a simulated microlensing amplification pattern for a ΛCDM Universe with the dark matter made up of $0.3M_\odot$ compact bodies. The input parameters for this procedure, such as the mass of the lenses and the size of the quasar accretion disc, were derived from observations and not from optimized parameter fits. The resulting distribution of amplitudes after including the effects of microlensing closely matches that of the observed amplitude distribution for the quasar sample. The identity of the lenses is still uncertain, but the only plausible candidates appear to be stellar mass primordial black holes. The overall conclusion of the paper is that to understand the amplitude distribution of a large sample of quasar lightcurves it is necessary to include the microlensing effects of a cosmologically distributed population of stellar mass compact bodies.

**DATA AVAILABILITY**

The data upon which this paper is based are all publicly available and are referenced in Section 2.

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