THE SIGNATURE OF DARK MATTER IN QUASAR LIGHT CURVES

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The idea that dark matter in the form of small compact bodies (most plausibly planetary mass primordial black holes) betrays its presence by the microlensing of quasars, has been stimulated by statistical studies of quasar light curves and gravitationally lensed quasar systems. In this paper we review this evidence, and discuss the significance of the recent detection of a planetary mass microlensing event in the Galaxy by the MACHO group. We also look in more detail at the light curves themselves, and make the case that many show the characteristic morphology of caustic crossing events associated with a large optical depth of lenses. This supports the idea that a large fraction of the critical density is in the form of planetary mass compact bodies. The nature of such bodies is discussed, and it is argued that current work on the QCD phase transition suggests they are primordial black holes, although it is just possible that they are compact gas clouds.

1 Introduction

There are a number of lines of argument which suggest that a substantial amount of dark matter may exist in the form of compact bodies. Although many mass ranges are trivially ruled out from the gross effects which would be observed, the range from $10^{-6}$ to one $M_\odot$ is still largely unconstrained outside the Galaxy. Within the Galaxy, the MACHO and EROS projects suggest a complicated picture which has still not been finalised. In this paper we review the evidence favouring a significant population of compact bodies in the subsolar and planetary mass range. This comes largely from an analysis of quasar light curves, both single objects and gravitationally lensed systems, to test the hypothesis that variation is caused by the microlensing effects of a large population of small bodies. It is possible that one such body has recently been detected by the MACHO group in the Galaxy. If quasar microlensing is a general phenomenon, the mass of the lenses can be estimated at $\sim 10^{-3} M_\odot$. Further arguments suggest that the lenses are most plausibly primordial black holes and make up a large fraction of the cosmological critical density.

2 Observational Evidence for Microlensing
2.1 Statistical Analysis of Quasar Light Curves

Until a few years ago it was generally assumed that observed variations in quasar brightness were caused by intrinsic changes in the flux output of the quasar. For short variations of a few months, the observed timescales broadly match theoretical expectations, although precise mechanisms for the brightness changes are still hard to specify. Long term variations of a few years, which appear to dominate quasar light curves, are much harder to explain as intrinsic variation, not only because of the timescale, but also other statistical properties. An alternative proposal by Hawkins was that the long term variation was caused by microlensing. A population of sub-stellar or planetary mass bodies along the line of sight would produce light curves similar to those observed, and the amount of material required would be a large fraction of the cosmological critical density. By measuring the timescale of variation and making some assumptions about the kinematics of the microlensing bodies it is possible to estimate their characteristic mass. This turns out to be around the mass of Jupiter, with an uncertainty of at least an order of magnitude.

Variation caused by microlensing has a number of statistical properties which can be tested by analysis of a large sample of quasar light curves. The tests include measures of chromatic variation, statistical symmetry, luminosity effects and time dilation (intrinsic variation should show an increase of timescale with redshift). Results of these tests and others have been published, and in all cases are consistent with the predictions of microlensing. While such an approach cannot easily rule out the unconstrained possibilities of intrinsic variation, the results are hard to model on that basis.

2.2 Microlensing in Multiply Lensed Quasar Systems

Quasars in multiply lensed systems are known to vary in two distinct modes. The best known of these is when all images vary in the same way with identical light curves, but with time differences for each image. This is well understood to be the effect of intrinsic variation in the parent quasar, which due to small differences in light travel time results in temporal displacement of the light curves. However, in all quasar systems where there is sufficiently comprehensive monitoring, additional variation in individual images is also seen. There is general consensus that this has to be the effect of microlensing, although the nature and location of the microlensing bodies is still open to debate.

One might argue that since microlensing is seen in every quasar system, it is a generic property of all quasars, and is a manifestation of the effect seen in the statistical monitoring of samples of single quasars. The problem with this line of argument is that macrolensed quasars inevitably have a massive
galaxy close to the line of sight which may be the source of the microlensing. Thus lensed quasars may not be representative of the quasar population as a whole. In fact this argument is not as secure as it might seem. For a high probability of microlensing there must be approaching a critical optical depth to lensing in microlensing bodies along the line of sight. This implies that the galaxy is largely made up of microlensing bodies, and that they make up the dark matter. The microlensing cannot be caused by normal stars which only make up a few percent of the galaxy’s mass. The only alternative is that the microlensing is taking place more generally along the line of sight as for other quasars, so either way we must conclude that the dark matter is in the form of compact bodies.

2.3 Detection of Planetary Mass MACHO’s in the Galaxy

If dark matter is in the form of compact bodies, one might plausibly expect to detect them in the halo of the Galaxy. It is well known that the MACHO and EROS projects claim to have detected a population of compact bodies sufficient to make up around half the mass of the halo, and it is tempting to associate them with bodies responsible for quasar microlensing. The problem with this is that the MACHO mass is estimated at around half a solar mass, whereas microlensing of quasars suggests a mass of $\sim 10^{-3}M_\odot$. At the moment it seems that these two mass estimates cannot be made compatible.

Until recently no planetary mass bodies had been detected by the MACHO project, which they claim implies an upper limit of 20% of the mass of the halo in such objects. However, in the Galactic bulge a short timescale event was recently observed, with an estimated mass about twice that of Jupiter. This single detection taken at face value implies a large mass density of such objects, and a density enhancement in the bulge consistent with their identification as the dark matter component. If this is a detection of one of the objects responsible for quasar microlensing then the limits for the halo, if correct, imply that the mass distribution is flatter than might be expected.

2.4 Caustic Crossings in Quasar Light Curves

Although statistical tests of quasar light curves are important probes of the nature of the variation, and can tightly constrain models of both intrinsic variability and microlensing, they do not make use of the detailed information available in the observations. When quasars are observed through a large optical depth for microlensing, the lenses combine non-linearly to produce caustic patterns. This effect has been simulated numerically and analytically by
several groups, and it is found that characteristic double spiked patterns are formed in the quasar light curves as the source traverses the caustics.

Examples of such caustic crossings have recently been looked for in a large sample of quasar light curves. The double spiked structure appears to be a feature of many of the light curves, but their interpretation as caustic crossings seems inconclusive. However two light curves, illustrated in Fig. 1, stand out as being very plausible caustic crossing events. In the light curve in the top panel the blue light rises very rapidly by more than a magnitude to a cusp like feature; the red light actually starts to increase three years earlier, but does so smoothly, and does not achieve the same amplitude as the blue. After six years a similar pattern in reverse appears to occur. In the bottom panel a somewhat similar picture is seen. It is very hard to think of a plausible model for this behaviour in terms of intrinsic variation, although microlensing provides a straightforward explanation. The blue light would come predominantly from a blue compact nucleus of an accretion disk, essentially unresolved by the lenses. It would thus show the characteristic features of caustic crossing events. The red light on the other hand would come mostly from the much larger area of the whole accretion disk. This would be resolved by the lenses; the magnification would commence earlier but never achieve the same amplitude as the blue, and there would be no sign of caustic crossing features.

3 Theoretical Constraints

The arguments in the previous section all support the idea of a population of compact bodies around the mass of Jupiter sufficient to make up a significant fraction of the cosmological critical density. It is just possible that they could be baryonic. By pushing baryon synthesis constraints to their limit with inhomogeneous nucleosynthesis, and reducing the required optical depth to microlensing to the minimum that will produce the observed level of variation one might be able to compromise on a cosmological density $\Omega = 0.3$. The idea that the bodies could be ordinary planets seems completely implausible, but there is the interesting possibility that they could be planetary mass gas clouds. This solution has the advantage that it explains why it has been so hard to detect the bodies in the halo, as these gas clouds would be too large to micolens LMC stars.

An alternative possibility which we have argued in earlier papers is that the microlensing bodies are primordial black holes. Far fetched though this idea might sound, it provides a plausible explanation of the observations, is consistent with baryon synthesis constraints, and fits well with current work on black hole formation in the QCD phase transition. The black holes would
Figure 1: Light curves for two quasars showing all the characteristics expected of caustic crossing events. Filled and open circles are blue and red passband measures respectively. Error bars are based on measured photometric errors.
behave as cold dark matter and make up sufficient mass to account for dark matter on a large scale.

4 Discussion and Conclusions

In this paper we have reviewed the evidence implying that quasars are being microlensed by a population of Jupiter mass bodies. Each line of argument is probably not conclusive in itself, but taken together they provide a structure which is hard to circumvent. There seems to be no doubt that at least some quasars are being microlensed; the residual question is how widespread is the phenomenon. This in turn directly relates to the amount of dark matter which can be made up of the microlensing bodies. At present the mass density would appear to be close to the cosmological critical density. There is also some considerable uncertainty in the characteristic mass of the bodies. The best estimate at the moment seems to be around $10^{-3}M_\odot$ but this could be out by at least an order of magnitude either way.

If one accepts the strong arguments that dark matter must at least in part be in the form of non-baryonic material, then the two most plausible possibilities seem to be some sort of SUSY particle, or primordial black holes. The main problem with the idea of SUSY particles is that at the moment their properties are largely unconstrained, and they are close to being undetectable. Primordial black holes on the other hand can be detected in a predictable way, and indeed as argued in this paper, this may already have happened. The circumstances in which they might form are becoming better understood, as well as the mass function. The only other possibility is that the dark matter is baryonic, and in this case the best candidates would appear to be compact planetary mass gas clouds.

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