The Direct Detection of Non-Baryonic Dark Matter in the Galaxy?

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Abstract

It has been argued in a number of recent papers that dark matter is in the form of Jupiter mass primordial black holes which betray their presence by microlensing quasars. This lensing accounts for a number of characteristic properties of quasar light curves, in both single quasars and gravitationally lensed multiple systems, which are not explained on the basis of intrinsic variation. One prediction of this idea is that Jupiter mass bodies will be detected by the MACHO experiment as short events of about 2 days duration, although the expected frequency of detection is still very hard to estimate. However, the recent report by the MACHO group of the detection of a Jupiter mass body in the direction of the Galactic bulge is consistent with this prediction, and is possibly the first direct detection of non-baryonic matter in the Galaxy.

1 Introduction

The idea that non-baryonic dark matter might be in the form of Jupiter mass primordial black holes has recently been put forward (Hawkins 1993, 1996) on the basis of an analysis of quasar light curves. Long term variations are shown to possess the characteristics expected from microlensing, such as achromaticity and lack of time dilation, and a case is made that the variations are not intrinsic (Hawkins & Taylor 1997). A new approach
has involved the analysis of multiply lensed quasars, where microlensing is known to take place (Schild 1996), and the question is to what extent they constitute typical lines of sight. It is argued (Hawkins 1997a, 1997b, 1997c) that the stellar population of the lensing galaxy is not in general capable of producing the observed variations.

If this picture is correct then the mass of the microlensing bodies can be obtained from the timescale of variation of the quasars and is found to be $\sim 10^{-3}M_\odot$, about the mass of Jupiter. To produce continuous variation in the quasar light, their mass density must be around the cosmological critical density. Baryon synthesis constraints imply that they must be non-baryonic, and the most plausible interpretation is that the lenses are primordial black holes created in the early universe during the quark/hadron phase transition (Hawkins & Taylor 1997).

2 MACHO Observations

On the basis of the quasar observations one can only conclude at present that the lenses have the critical density on the large scale. To probe smaller scales, the MACHO experiment has become well known as a method for detecting compact bodies in the halo and bulge of the Galaxy by means of gravitational microlensing (Alcock et al. 1993). The idea is to observe the amplification of distant stars by the rare transits of nearer bodies across the line of sight. A detailed description of the technique has recently been published (Alcock et al. 1997), together with the latest results in the direction of the Large Magellanic Cloud. The current conclusion is that the Galactic halo contains at least 50% of its mass in the form of half-solar mass bodies, and the most plausible explanation seems to be that they are white dwarfs (Adams & Laughlin 1996), left over from a very early phase of star formation.

Although there is a clear prediction that the Jupiter mass bodies should eventually be detected in the MACHO survey (Hawkins 1996, 1997d), the question of the detection frequency has remained an open one as it has not been clear to what extent non-baryonic dark matter will cluster into the Galactic halo. The detection of 50% of the halo mass in the form of half-
solar mass bodies suggests that it is in fact largely baryonic, and so the need for non-baryonic matter to cluster on that scale is lessened, whether it is in the form of SUSY particles or primordial black holes.

As originally conceived, the MACHO programme was most sensitive to objects in the range $0.1M_\odot$ to $0.01M_\odot$, producing events lasting several tens of days, but the team has recently attempted to extend their coverage down to planetary mass ($10^{-3}M_\odot$) objects giving rise to microlensing events lasting from 0.3 to 3 days. This was done by analysing data from nights where more than one observation of the same stars was available (Alcock et al. 1996). As the search for microlensing events is extended into the planetary mass regime, a number of new factors come into play. These include the effect of the finite size of the source stars, which will eventually decrease the observed amplitude of the lensing event, and the much smaller number of samples covering each event. One would expect a discrete drop in efficiency as the timescale decreases to two or three days, and most of the variation takes place in daylight when it cannot be observed. The MACHO group claim to have allowed for these effects (Alcock et al. 1996) by estimating their efficiency with a Monte Carlo simulation. This is certainly a useful approach, but it is not clear how reliable the results are, as there is no indication of a discrete change in the probability function as the day and night times become significant. Nonetheless, in what follows we will adopt the figures published by the MACHO group.

So far, no planetary mass objects have been detected in the halo, and a limit of around 20% has been put on their contribution to the halo mass (Alcock et al. 1997). However, one such event has recently been reported in the Galactic bulge where the event rate is much higher (Bennett et al. 1997). The event has a duration of two and a half days, and the MACHO group estimate the mass of the lensing body to be about $2M_{\text{Jup}}$, close to the mass found from quasar microlensing. The light curve comprises 3 amplified measures in each colour and appears to be achromatic, but the small number of points leaves some room for doubting its classification as a microlensing event. Again, in what follows we will accept the verdict of the MACHO team.

The event stands well away from the distribution of other (presumably stellar) lensing events. The MACHO group estimate that it has only a small
probability of being a part of the tail of stellar mass lenses, and conclude
that it might be a planet in a distant orbit, or one which has become de-
tached from a planetary system. We shall see below that the statistics do
not favour this interpretation. However, the mass and distribution are as
predicted from the analysis of the quasar light curves, where the population
of microlensing bodies is distinct from the stellar distribution. If the mi-
crolensing picture is correct, then sooner or later the dark bodies must be
detected by the MACHO experiment. It thus seems plausible that this short
event is the first detection in the Galaxy of one of the bodies responsible for
quasar microlensing on a larger scale.

3 Discussion

If the two and a half day MACHO event is caused by one of the Jupiter
mass black holes, it is possible to estimate the density enhancement over
the critical density that this would represent. First we can calculate the
number of lenses as a fraction of the stellar population. If we adopt the
published detection efficiency as a function of mass (Alcock et al. 1997) it
will be seen that the probability of detection of a 2 day event is about 0.1
that of a 20 day event. In mass terms, the detection of a 0.001$M_\odot$ body is
10% as likely as that of a 0.1$M_\odot$ body. To deduce the actual proportion of
0.001$M_\odot$ to 0.1$M_\odot$ bodies one must also allow for the size of the Einstein
disks, which is not incorporated in the efficiency values since an ‘event’ is
defined as a star passing within the Einstein disk of a lens. This goes as $\sqrt{M}$
and thus effectively decreases the relative detection rate of 0.001$M_\odot$ bodies
by a further factor of 10. As for the actual detection rate in the bulge, we
see (Bennett et al. 1997) that approximately 100 stellar mass objects have
been detected compared with the one Jupiter mass body. Combining these
two figures implies that the Jupiter mass bodies number about the same as
the stellar population where the microlensing is taking place. If the bodies
are detached planets or planets in distant ($>10AU$) orbits, the implication
is that on average every star gives rise to such an object. This seems implau-
sible and would not appear to be consistent with the statistics of planetary
systems as they are currently understood (Marcy & Butler 1997).
If we take the stellar space density in the vicinity of the sun at around 0.12 pc\(^{-3}\) (Tinney 1993) and the scale length of the disk as 2.3 kpc (Ruphy et al. 1996), then the space density of stars half way to the Galactic centre at the most probable position for microlensing is 0.8 pc\(^{-3}\). It has been argued above that the Jupiter mass objects have the same space density as this, implying a mass density of about 10\(^{-3}\)M\(_{\odot}\) pc\(^{-3}\). Taking the cosmological critical density as 10\(^{-7}\)M\(_{\odot}\) pc\(^{-3}\), this represents a density enhancement \(\delta \rho/\rho \sim 10^4\), comparable to the over-density of galactic halos. The mass density of the Galactic halo out to 60 kpc is about 10\(^{12}\)M\(_{\odot}\) (Hawkins 1984), an average mass density of 10\(^{-3}\)M\(_{\odot}\) pc\(^{-3}\). This is about the same as the mass density of Jupiter mass bodies we have deduced from the MACHO experiment in the direction of the bulge, which if distributed uniformly could thus account for the dark matter in the halo. However, a flat halo profile would be inconsistent with the MACHO results towards the LMC. This experiment limits the average space density of 10\(^{-3}\)M\(_{\odot}\) bodies in the halo to around 10\(^{-2}\)pc\(^{-3}\) (Alcock et al. 1997, Renault et al. 1997), a factor of 100 down on the density near the bulge. If the decline were to follow a power law, then taking into account the integral constraint of the mass of the halo out to the LMC, it would have an index of around \(-2\), somewhat flatter than the index of \(-3\) for halo stars (Hawkins, 1984). This is in line with more general expectations for the distribution of non-baryonic dark matter. Although the MACHO results appear to rule out a halo dominated by non-baryonic material out to around 25kpc, the implication is that it may well predominate further out.

4 Conclusions

In this paper we have examined the possibility that the recent detection of a planetary mass body by the MACHO group could be one of the Jupiter mass primordial black holes recently proposed as the constituent of non-baryonic dark matter. The detection accords with predictions made on the basis of studies of quasar variability interpreted as the effects of microlensing. The mass density implied by this detection is in line with the density enhancement associated with galactic halos.
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