Probing dark matter with X–ray binaries

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ABSTRACT

Low-mass X-ray binaries (LMXBs), which occur in old stellar populations, have velocities exceeding those of their parent distribution by at least $20\,\mathrm{km\,s^{-1}}$. This makes them ideal probes for dark matter, in particular in dwarf spheroidals (dSph), where the LMXBs should penetrate well outside the visible galaxy. We argue that the most likely explanation of the observation of LMXBs in the Sculptor dSph by Maccarone et al. (2005) is the presence of a dark matter halo of $\gtrsim 10^9\,\mathrm{M_\odot}$, corresponding to a total-mass to light ratio of $\gtrsim 600(M/L_V)_\odot$. In this case there should be an extended halo of LMXBs which may be observable.

Key words: galaxies: dwarf, galaxies: structure, galaxies: haloes, X–rays: binaries

1 INTRODUCTION

A recent study by Maccarone et al. (2005) reports the detection of five X–ray binaries with $L_X > 6 \times 10^{33}$ erg s^{-1} in the Sculptor dwarf spheroidal (dSph) galaxy. Their membership of Sculptor is secure, as they are optically identified with counterparts in the catalogue of Schweitzer et al. (1995) which have appropriate proper motions and photometry. Given the old stellar population of Sculptor (see below) these must be low–mass X–ray binaries (LMXBs). In the Milky Way, LMXBs are observed to have relatively high space velocities $v_{\mathrm{sp}} \sim 20 - 100\,\mathrm{km\,s^{-1}}$ (e.g. Brandt & Podsiadlowski 1995 and references therein; see Podsiadlowski et al. 2005 for a recent review) resulting from the recoil of the system after the supernova creating the compact component. These velocities are far above the stellar velocity dispersion $\sim 11\,\mathrm{km\,s^{-1}}$ in Sculptor, so it is interesting to ask how Sculptor can retain any LMXBs at all.

2 THE NATURE OF THE LMXBS IN SCULPTOR

The observed LMXBs in Sculptor are relatively faint, and are probably quiescent transients. Given a visible mass[1] $\sim 10^7\mathrm{M_\odot}$ for Sculptor, the incidence $\sim 5 \times 10^{-7}\mathrm{M_\odot^{-1}}$ of observed LMXBs per stellar mass is significantly higher than that $(10^{-8} - 10^{-9}\ \mathrm{M_\odot^{-1}})$ of much brighter LMXBs in the large sample of elliptical galaxies studied by Gilfanov (2004). This agrees with the deduction of Piro & Bildsten (2002) that the bright X–ray population of early–type galaxies probably consists of the long–lasting outbursting transients predicted by simple theories of the accretion disc outburst (King et al. 1996, see also Ritter & King 2002).

The argument is straightforward: the low–mass donors ($\lesssim 1\mathrm{M_\odot}$) in LMXBs cannot sustain the mass accretion rates $\sim 10^{-9} -$

$10^{-8}\mathrm{M_\odot}$ yr^{-1} needed to power the bright sources in early–type galaxies for a significant fraction of their ages, so accretion must be intermittent. The relative incidence of faint X–ray sources in Sculptor and of bright ones in ellipticals gives a lower limit to the ratio of quiescent to outburst timescales (= 1/duty cycle) as $\gtrsim 200$. This would allow even the brightest sources in ellipticals to have ages comparable with their host galaxy. Moreover it agrees with the completely independent estimate of the duty cycle in long–period transients by Ritter & King (2002), who compared the observed numbers of long–period neutron–star transients with their descendants (wide binaries containing a millisecond pulsar and a low–mass white dwarf). This agreement suggests that Sculptor has retained most of its X–ray binaries. We now ask how.

We can discard two possibilities. First, there is little reason to suppose that supernova kicks have vastly different properties in Sculptor and the Milky Way. Although the metallicity is low (see below) the gross properties of LMXB kicks are not sensitive to such details: kick velocities are of order the orbital velocities in the pre–supernova binary because a symmetrical supernova explosion carries off a mass comparable to that of the remaining binary with the velocity of the exploding component. Anisotropies are important in keeping bound some systems which would otherwise unbind, but do not significantly alter this fact. The only way to increase the retention rate on these lines is to remove the supernova explosion altogether, i.e. to argue that the Sculptor LMXBs are all black–hole systems which went through non-explosive collapses instead of supernovae. However unless there is a special mechanism very strongly favouring black–hole versus neutron–star formation we would require a very high formation rate for LMXBs. Even then, black–hole LMXBs in the Milky Way do appear to have kicks of 20 km s^{-1} or more (Tauris & van den Heuvel 2003) which would make them hard to retain in Sculptor. In line with these arguments, low metallicities appear if anything to lower LMXB incidence: Kundu et al. (2002) and Bregman (2006) show that globular cluster with lower metallicities have fewer LMXBs. Rather than a systematic difference in kick velocities, this effect probably in-

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[1] Assuming a mass-to-light ratio of $\sim 6(M/L_V)_\odot$ and using $L_V = 1.5 \times 10^6\mathrm{L_\odot}$ for Sculptor, see Section 3.1 below.

dicates that metal–rich clusters have higher LMXB tidal capture formation rates.

Second, it is implausible to argue that the observed LMXBs are not bound to Sculptor: they would escape from a region of size $R = R_{kpc}$ kpc on a timescale $t_{esc} \sim R/v_{kick} \lesssim 2 \times 10^7 R_{kpc} (50 \text{ km s}^{-1}/v_{kick})$ yr after the supernova, in many cases not even evolving into contact and turning on as LMXBs until well outside the galaxy. The required LMXB formation rate per unit galaxy mass $\sim 5/(t_{esc} M_{gal}) \sim 2.5 \times 10^{-15} \text{ yr}^{-1} \text{ M}_\odot^{-1}$ would be higher than inferred for the Milky Way. There, with an LMXB population of $\sim 100/d$ and LMXB lifetimes ~ 1 Gyr one gets $10^{-18} d^{-1} \text{ yr}^{-1} \text{ M}_\odot^{-1}$), where d is the transient duty cycle. The very small values $d \lesssim 10^{-3}$ needed to make this agree with Sculptor would create problems (cf. Ritter & King 2002) in spinning up neutron stars to millisecond periods in LMXB descendant binaries, because the neutron stars would accrete very little mass during the rare but generally highly super–Eddington outbursts. We note further that the pre–supernova lifetime of any star massive enough to make a neutron star is (conservatively) $\lesssim 10^8$ yr, so any burst of star formation making an overabundance of LMXBs would have to have been more recent than that, which is ruled out by observation (see below).

A rather more promising idea, but still with difficulties, is that there might exist a class of LMXB with low–velocity kicks which Sculptor could retain, beyond the minority of black–hole systems referred to above. Podsiadlowski et al. (2005) indeed identify a low–velocity subset of high–mass X–ray binaries, but these can no longer be present in Sculptor's old stellar population. Apart from the minority of black–hole systems discussed above, there appear to be very few LMXBs with low–velocity kicks. Thus if such a class exists it is clearly rather small, and one would again face the problem of a high required birthrate of LMXBs. Worse, one would require a still smaller transient duty cycle ($d \lesssim 10^{-3}$) to match the incidence of LMXBs in Sculptor with that in ellipticals, running into the same problem in spinning up neutron stars to millisecond periods noted above.

These attempted explanations all tried to ascribe reduced space velocities to the Sculptor LMXBs in order to compensate for the galaxy's feeble apparent gravity. There appears to be only one fairly straightforward explanation for the Sculptor LMXB population observed by Maccarone et al. (2005). The galaxy must have much stronger gravity, i.e. dark matter.

3 DARK MATTER IN DWARF SPHEROIDALS

In recent years evidence has grown for the existence of extended massive dark-matter haloes around some of the dSph satellites of the Milky Way. Extensive radial–velocity data, for example for the Draco dSph, suggest these objects are embedded in enormous dark–matter haloes (Kleyna et al. 2001), resulting in total-mass to light ratios well in excess of $100 \, (M/L_V)_\odot$. Moreover, such extended dark–matter haloes make the star–formation process more comprehensible (Mashchenko, Couchman & Sills 2005) and alleviate the "missing satellites" problem of cold dark matter cosmologies.

3.1 The Sculptor dwarf spheroidal

Sculptor appears to be the only Galactic dSph with no young stellar population (that was why Maccarone et al. chose it to search for LMXBs). Its stellar population is as old as that of globular clusters,

but with a more extended star formation period, although a small tail of residual star formation until about 2 Gyr ago cannot be ruled out (Monkiewicz et al. 1999).

Sculptor's stellar population contains two kinematically and spatially distinct components of different metallicity, also reflected in a bi-modality of its horizontal branch (e.g. Tolstoy et al. 2004). The "metal rich" ([Fe/H] > -1.7) component is more centrally concentrated than the metal poor component ([Fe/H] < -1.7). The line–of–sight velocity dispersion σ of the former is $\approx 6 \text{ km s}^{-1}$ (Armandroff & Da Costa 1986; Queloz, Dubath & Pasquini 1995; Tolstoy et al. 2004), while the latter has $\sigma \approx 11 \text{ km s}^{-1}$ (Tolstoy et al. 2004; Clementini et al. 2005).

From their observation of $\sigma \approx 6 \text{ km s}^{-1}$, Queloz et al. (1995) derived a central mass–to–light ratio M/L of $13\pm6 \, (M/L_V)_\odot$ and a total mass (within the visible galaxy) of $(1.4 \pm 0.6) \times 10^7 \text{ M}_\odot$ (assuming a single stellar component). The same authors report an absolute magnitude of $M_V = -10.7 \pm 0.5$ corresponding to $L_V = (1.5\pm0.7)\times10^6 \text{L}_\odot$ and resulting in a mass-to-light ratio of 10 ± 6, which is perfectly consistent with an old stellar population, suggesting that dark matter is in fact *not* significantly contributing in the central region.

Although there has been no detailed modelling of the implications of the bimodal stellar population with different σ, we may roughly assess the consequences by noting that the mass–to–light ratio is proportional to σ^2. Thus, from these data we may expect M/L of up to $\sim 50 \, (M/L_V)_\odot$, corresponding to a mass of $\sim 6 \times 10^7 \text{M}_\odot$ within ~ 1.5 kpc (the apparent extent of the stellar population).

However, if the matter distribution of Sculptor did not extend beyond this radius, one would expect the Galactic tidal field to distort Sculptor's outer regions significantly, which is not observed (Coleman, Da Costa & Bland-Hawthorn 2005). This lack of tidal distortion may therefore be interpreted as indirect evidence for the presence of a more extended dark–matter halo, like the ones claimed for Draco and Ursa Minor, which protects the dSph from Galactic tides. The very fact that Sculptor possesses two distinct stellar populations, evidently formed in two starbursts, also strongly suggests that it is surrounded by an extended dark–matter halo. This is needed to prevent the loss of all the gas expelled during the first starburst in a galactic wind.

3.2 LMXBs as probes of dark matter

The binary kick velocity is typically $20 - 100 \text{ km s}^{-1}$, well in excess of the velocity dispersion found in a dSph. The LMXBs of a dSph should therefore be kicked out of the visible galaxy. If the dSph are surrounded by an extended dark–matter halo, some of the LMXBs would still remain bound, orbiting on highly eccentric, almost plunging, orbits. Otherwise most would escape and we would only see those which received a rather small velocity kick. Thus, an extended dark–matter halo for dSph galaxies implies a similarly extended halo of LMXBs, a prediction that can be observationally tested. Since the LMXBs would spend comparatively little time in the visible galaxy, there should be a large number of them further out. The detectability of this halo obviously depends on the surface density of the LMXBs, and thus on the kick velocities and the dark matter distribution.

Because the LMXBs should form a distribution much more extended than their parent population, they are ideal probes for more detailed investigations of dSph dark–matter haloes. In particular, their velocities (radial and proper motions) may be measured enabling in situ quantitative modelling of the dark–matter haloes.
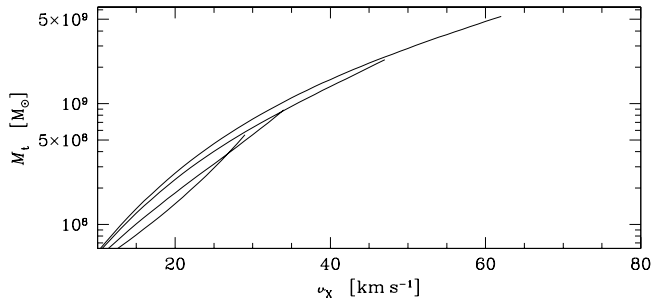
Figure 1. The minimum mass of an extended dark–matter halo for Sculptor that is required to hold on to an LMXB with velocity v_X at radius 1 kpc for haloes with core radii r_c of 0.7, 1.5, 3, and 5 kpc. The haloes are assumed to have mass $5 \times 10^7 M_\odot$ within 1.5 kpc. The curves end to the right when the required truncation radius r_t exceeds 15 kpc (the larger the core radius, the larger the maximum v_X still bound).

3.3 LMXBs in Sculptor

We now try to estimate roughly what kind of dark–matter halo is required to keep the LMXBs observed in Sculptor bound. We model the halo as a sphere with cumulative mass

$$GM(< r) = v_0^2 \frac{r^3}{r^2 + r_c^2},$$

which corresponds to a density profile similar to the pseudo–isothermal sphere. Here, v_0 is the (asymptotic) circular speed and r_c the core radius. We assume that the dark mass within the visible galaxy is $5 \times 10^7 M_\odot$, in agreement with our above estimate for the mass–to–light ratio, requiring

$$v_0 = 12 \, \text{km s}^{-1} \sqrt{1 + \left(\frac{r_c}{1.5 \text{kpc}} \right)^2}.$$

If the halo is truncated at radius r_t, then the velocity $v_{esc}(r)$ required at radius $r < r_t$ to escape to radius r_t (where the LMXB would be stripped from the dark–matter halo by the Galactic tidal field) is

$$v_{esc}^2(r) = v_0^2 \ln \frac{r_t^2 + r_c^2}{r^2 + r_c^2}.$$

In Figure 1 we plot the corresponding halo mass required to hold on to an LMXB moving out from $r = 1$ kpc with velocity v_X for various choices of r_c. Evidently, this figure suggests that it would be difficult for a dSph to hold on to LMXBs with velocities of $50 \, \text{km s}^{-1}$ or higher unless it has a total mass in excess of $10^9 \, M_\odot$ (this is largely independent of details, such as the core radius of the dark matter or the initial position of the LMXB at the time of the kick). Since $10^9 \, M_\odot$ is about the dark mass discussed for dwarf spheroidals (e.g. Mashchenko et al. 2005), we would thus expect these galaxies to hold on only to the LMXBs with lower velocities. This argument can, of course, be turned around to provide a mass estimator for the dSph dark–matter haloes via the escape–velocity argument or more sophisticated dynamical modelling, usually applied to the Milky Way.

4 DISCUSSION

We have argued that the most likely explanation for the presence of LMXBs in Sculptor is a dark matter halo of $\gtrsim 10^9 \, M_\odot$. This is $\gtrsim 100$ times the observed stellar mass and corresponds to a total-mass to light ratio of $\gtrsim 600 (M/L_V)_\odot$. This value is comparable to

that proposed for the Draco dSph as a result of simulations of tidal stripping by Read et al. (2005, 2006). We argued further that in this case there should be an extended halo of LMXBs which might be observable. An estimate of the total number of LMXBs in this halo would constrain the transient duty cycle still further.

The obvious test of our ideas would come from measuring at least the radial velocities of the observed LMXBs. This should be possible given that Maccarone et al. (2005) were able to make optical identifications of some of these sources, and would be extremely interesting whatever the result. If the deduced space velocities are high, this would confirm the presence of a very massive dark matter halo. If not, this would have important implications for understanding transient duty cycles and LMXB formation in general.

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