Acta Astronautica 104 (2014) 472–476

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Extrasolar solar-sail trajectories and dark matter

Gregory L. Matloff

Department of Physics, New York City College of Technology, CUNY, 300 Jay St., Brooklyn, NY 11201, USA

A R T I C L E I N F O

Article history:
Received 28 December 2013
Received in revised form
24 March 2014
Accepted 30 March 2014
Available online 4 April 2014

Keywords:
Solar sail
Dark matter
Pioneer Anomaly
WIMPS

A B S T R A C T

Hyper-thin, high-speed solar-photon sail space probes exploring the Sun's Oort comet cloud could also be used to set an upper bound to the concentration of WIMPS (weakly interacting massive particles), one of the suggested (but unconfirmed) forms of dark matter within the vicinity of the solar system. Newton's Shell Theorem would be applied to determine variations in apparent solar mass as the probe moves further out from the Sun. Application of this technique to the trajectories of Pioneer 10/11 reveals that the upper limit to WIMP concentration within ~60 AU of the Sun is ~0.2 Earth masses, as revealed in studies of the Pioneer Anomaly. If the published accuracy of the Pioneer acceleration measurements can be increased by an order of magnitude, probe trajectory measurements out to ~10,000 AU may confirm or falsify the hypothesis that WIMP mass within the solar vicinity is ~3X star mass. It is shown that a space-manufactured ~40-nm thick beryllium hollow-body solar sail deployed from a ~0.07 AU perihelion is a candidate spacecraft for such a mission. Possible science-team organization strategy for a ~100-year mission to ~10,000 AU is discussed.

1. Introduction: deep-space exploration destinations

Contemporary and near-term solar photon sails have been proposed to launch exploratory missions to various solar system destinations and the heliopause at around 200 AU from the Sun. [1,2]. In the not-too-distant future, possibly before mid-century, sail technology may have advanced enough that space agencies may consider sail-launched probes to the Sun's inner gravity focus at and beyond 550 AU [3].

Some research has been conducted on hyper-thin space manufactured all-metal sails that could ultimately serve as true starships, propelling robots or humans on millennial expeditions to nearby stars [4,5]. Although such ventures are far in the future, it would be nice if some compelling destination intermediate between 550 AU and the nearest stars at about 240,000 AU existed, so that small-scale interstellar craft could be built and tested in the not-too-distant future.

In long range planning for post-2040 space exploration, NASA has considered the possibility of designing a robotic Oort-cloud probe to explore the inner fringes of the Sun's Oort comet cloud, further than 1000 AU from the Sun [6]. But Sedna, a member of the Oort cloud with a perihelion of about 76 AU and an aphelion of about 1000 AU is currently only about 100 AU from the Sun [7]. A near-term Earth-launched sail such as those proposed for the heliopause mission could visit this object in a human lifetime. Because of Sedna's eccentric orbit and current accessibility, it may be difficult to make a compelling case for a dedicated Oort-cloud probe.

But there is a compelling alternative justification. It has been known for at least seven decades that the kinematics of stars in the Milky Way galaxy is not what one would expect from application of Newtonian gravitational theory. Instead of stars farther from the galactic center revolving less rapidly than those closer in, as do planets in our solar

E-mail address: GMatloff@citytech.cuny.edu

http://dx.doi.org/10.1016/j.actaastro.2014.03.019
0094-5765/

system, stars farther out move faster. Stars move around the galaxy almost as if they are attached to the spokes of an invisible wheel.

Some have attempted to explain this anomaly using modifications to the inverse-square nature of universal gravitation. But a problem with this approach is that different modifications seem necessary at different astrophysical distances [8]. Others have suggested that familiar paradigms of physical thought may require substantial revision [9].

Many astrophysicists take the conservative approach that a mysterious form of matter dubbed “dark matter” is a possible explanation for anomalistic stellar motions [10]. This dark matter might out-mass normal matter by a factor of three or four to one and comes in two possible forms: MACHOS (massive halo objects) and WIMPS (weakly interacting massive particles).

Advocates of MACHOS must deal with the fact that gravitational lens observation has not revealed a large number of invisible objects in the galactic halo and globular clusters in the galactic halo do not appear to be disrupted by large numbers of invisible, stellar-massed objects or brown dwarfs.

But WIMPS have their issues as well. For WIMPS to produce the necessary stellar-motion anomalies and remain undetected, these particles must be invisible and non-reactive with ordinary matter. As evidenced by accurate and exhaustive trajectory analysis of humanity's first extra-solar probes, Pioneer 10 and 11, it seems unlikely that a large cloud of dark matter is in the solar system, at least to a distance of 80 AU from the Sun, as is further discussed below.

If WIMPS do not gather in circum-stellar clouds, they must be more-or-less uniformly distributed in space. The following sections of this paper demonstrate that very accurate observations of the trajectory of a sail-launched probe to 10,000 AU might allow for the setting of an upper limit to WIMP density in the Sun's galactic vicinity.

2. Dark matter and interstellar probe trajectories

We begin this analysis of WIMP density determination by considering the volume of interstellar space dominated by the Sun, Since the Sun's mass is 1.99×10^{30} kg [10] and the distance to the Sun's nearest known stellar neighbor is about 4 light years, the Sun dominates a volume of 2.84×10^{49} m^3. The density of dark matter WIMPS in this volume is:

$$\rho_{dm} \approx 7 \times 10^{-20} \kappa \text{ kg/m}^3, \quad (1)$$

where κ is the local ratio of dark matter mass to solar mass.

By comparison, if we assume 0.1 proton or neutral hydrogen atom per cubic centimeter in the Sun's galactic vicinity, the local interstellar matter density is 1.67×10^{-22} kg/m^3. So “normal” interstellar matter in the solar vicinity can be safely ignored in this analysis.

Next, we apply Newton’s familiar Shell Theorem. If a spacecraft is a distance R_{au} Astronomical Units from the Sun, all spherically symmetric matter closer to the Sun than R_{au} can be treated as if it is centered on the Sun. All matter farther from the Sun than R_{au} can be ignored when estimating gravitational effects.

The volume of a sphere (V_{sp}) centered on the Sun with a radius ε AU is $1.4\,\varepsilon^3 \times 10^{34}$ m^3. The mass of dark matter within this sphere is therefore:

$$M_{dm} \approx 10^{15} \varepsilon^3 \kappa \text{ kg}. \quad (2)$$

Since this mass is assumed to be spherically symmetric and concentrated at the Sun's center from the point-of-view of gravity theory, the anomalous acceleration on a spacecraft towards the Sun at this distance from the Sun is estimated as:

$$a_{dm} = \frac{GM_{dm}}{(1.496 \times 10^{11} \varepsilon)^2} \approx 3 \times 10^{-18} \varepsilon\kappa \text{ m/s}^2, \quad (3)$$

where G is the gravitational constant.

Attention has been devoted to the trajectories of humanity's first extra-solar probes, Pioneer 10 and 11. Both of these probes were launched in the early 1970s. The final signal from Pioneer 10 was received on January 22, 2003, when this spacecraft was at a distance of 82 AU [11]. Pioneer 11 ceased operation in 1995, when it was more than 40 AU from the Sun [12].

Careful analysis of Pioneer 10 and 11 trajectory data between 40 and 60 AU reported in 1998 revealed an unexplained acceleration towards the Sun of 8.09×10^{-10} m/s^2 for Pioneer 10 and 8.56×10^{-10} m/s^2 for Pioneer 11, with errors of about 0.2×10^{-10} m/s^2 [13]. The accuracy of the acceleration estimates of these spin-stabilized space craft has been estimated as about 10^{-12} m/s^2, averaged over a period of 5 days [13].

The analysis of this so-called “Pioneer Anomaly” was supported by The Planetary Society [14]. The published results of the study indicate that the cause of the anomaly is differential thermal emissions from spacecraft surfaces, not a new physical phenomenon [15].

It would seem that the published accuracy estimate of the Pioneer 10/11 anomalous acceleration measurements, about 10^{-12} m/s^2, can be used to determine an upper estimate for the WIMP density within 60 AU. Applying Eq. (3), we find that $\kappa < 5600$. From Eq. (1), the maximum average density of dark matter within 60 AU of the Sun is 4×10^{-16} kg/m^2. This corresponds to a maximum dark matter mass within a sphere of 60 AU radius centered on the Sun is 1.2×10^{24} kg. This is about equal to 0.2 Earth masses.

Many previous observational searches for solar-system or near-solar-system WIMPS have yielded contradictory results, perhaps because of sensitivity or internal errors. For example, Anderson et al. in their examination of the Pioneer Anomaly estimate that WIMP mass out to 50 AU $> 3 \times 10^{-4}$ solar masses, or about 100 Earth masses. However, they admit that this result contradicts ephemeris data indicating that only $\sim 10^{-6}$ Sun masses of WIMPS exist within the orbit of Uranus [13].

In contrast, Steven Adler has applied data from the LAGEOS geodetic satellites to estimate WIMP mass between LAGEOS' orbital height (6000 km) and the Moon. He estimates WIMP mass in this region at about 4×10^{-9} Earth masses, which corresponds to about 0.2 Earth masses between Sun and Earth [16].