DARK MATTER ANNIHILATION AND DECAY PROFILES FOR THE RETICULUM II DWARF SPHEROIDAL GALAXY

Vincent Bonnivard1, Céline Combet1, David Maurin1, Alex Geringer-Sameth2, Savvas M. Koushiappas3, Matthew G. Walker2, Mario Mateo4, Edward W. Olszewski5, and John I. Bailey III4

1 LPSC, Université Grenoble-Alpes, CNRS/IN2P3, 53 avenue des Martyrs, F-38026 Grenoble, France; bonnivard@lpsc.in2p3.fr
2 McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA; mgwalker@andrew.cmu.edu
3 Department of Physics, Brown University, Providence, RI 02912, USA
4 University of Michigan, 311 West Hall, 1085 S. University Avenue, Ann Arbor, MI 48109, USA
5 Steward Observatory, The University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA

Received 2015 April 13; accepted 2015 June 9; published 2015 July 27

ABSTRACT

The dwarf spheroidal galaxies (dSph) of the Milky Way are among the most attractive targets for indirect searches of dark matter (DM). In this work, we reconstruct the DM annihilation (J-factor) and decay profiles for the newly discovered dSph Reticulum II. Using an optimized spherical Jeans analysis of kinematic data obtained from the Michigan/Magellan Fiber System, we find Reticulum II’s J-factor to be among the largest of any Milky Way dSph. We have checked the robustness of this result against several ingredients of the analysis. Unless it suffers from tidal disruption or significant inclination of its velocity dispersion from binary stars, Reticulum II may provide a unique window on DM particle properties.

Key words: dark matter – galaxies: individual (Reticulum II) – gamma rays: galaxies – methods: statistical – stars: kinematics and dynamics

1. INTRODUCTION

Along with the Galactic center and Galaxy clusters, the dwarf spheroidal galaxies (dSph) of the Milky Way have been identified as promising targets for indirect dark matter (DM) searches (see, e.g., Strigari 2013; Conrad et al. 2015). Their low astrophysical background, high mass-to-light ratio, and proximity make them compelling targets (Lake 1990; Evans et al. 2004). About 25 Galactic dSphs were known as of early 2015, and their observation by γ-ray telescopes has thus far shown no significant emission, leading to stringent constraints on ⟨v_ann⟩, the thermally averaged DM annihilation cross-section (Acaciari et al. 2010; Paiano et al. 2011; Abramowski et al. 2014; Geringer-Sameth et al. 2014; Fermi-LAT Collaboration 2015).

Recently, imaging data from the Dark Energy Survey have led to the discovery of nine new potential Milky Way satellites in the Southern sky (DES Collaboration et al. 2015; Koposov et al. 2015a). The nearest object, Reticulum II (Ret II, d ~ 30 kpc), is particularly intriguing, as evidence of γ-ray emission has been detected in its direction using the public Fermi-LAT Pass 7 data. Geringer-Sameth et al. (2015b) determined the probability of background processes producing the observed Ret II γ-ray signal to be between p = 0.01% and p = 1%, depending on the background modeling. An analysis of the new objects published simultaneously by Fermi-LAT Collaboration et al. (2015), based on the unreleased Pass 8 data set, reported no significant detection, though the strongest hint was for Ret II with p = 6%. Hooper & Linden (2015) subsequently performed a similar analysis with public Pass 7 data, finding a p value of 0.16%.

In any case, a robust determination of Ret II’s DM content is crucial in order to constrain particle nature of DM. Ret II was found to be a DM-dominated dSph galaxy from the independent chemodynamical analyses of Walker et al. (2015), Simon et al. (2015), and Koposov et al. (2015b). Here, we reconstruct the DM annihilation and decay emission profiles of Ret II from a spherical Jeans analysis applied to stellar kinematic data obtained with the Michigan/Magellan Fiber System (M2FS; Walker et al. 2015). We use the optimized Jeans analysis setup from Bonnivard et al. (2015a, 2015b), and compute the astrophysical J- and D-factors, for annihilating and decaying DM, respectively, from the reconstructed DM density profiles. We cross-check our results by varying different ingredients of the analysis and evaluate the ranking of Ret II among the most promising dSphs for DM indirect detection.

2. ASTROPHYSICAL FACTORS, JEANS ANALYSIS, AND DATA SETS

2.1. Astrophysical Factors

The differential γ-ray flux coming from DM annihilation (resp. decay) in a dSph galaxy is proportional to the so-called “astrophysical factor” J (resp. D; Bergström et al. 1998),

\[ J = \int \rho_{DM}^2(l, \Omega) \, dl \, d\Omega \]

which corresponds to the integration along the line of sight (LOS) of the DM density squared (resp. DM density) and over the solid angle \( \Delta\Omega = 2\pi \times [1 - \cos(\alpha_{int})] \), with \( \alpha_{int} \) the integration angle. This quantity depends on both the extent of the DM halo and the mass density distribution, and is essential for constraining the DM particle properties. All calculations of astrophysical factors are done with the CLUMPY code (Charbonnier et al. 2012), a new module of which has been specifically developed to perform the Jeans analysis.\(^6\)

2.2. Jeans Analysis

Several approaches have been developed to infer the DM density profile of dSph galaxies from stellar kinematics (see,

\(^6\) This upgrade will be publicly available in the new version of the software (V. Bonnivard et al. 2015, in preparation).
We use the vi package MultiNest (Feroz & Hobson 2008; Feroz et al. 2009, 2013), and we use the samples from the posterior PDFs to propagate the light profile uncertainty into the Jeans analysis. Figure 1 shows the fit to the projected stellar density profile of Ret II (dashed red line), with the contributions from Ret II itself and from the constant background (solid black and blue lines, respectively).

Kinematic data—we use the Ret II stellar kinematic data set from Walker et al. (2015), obtained with M2FS. It consists of projected positions and LOS velocities for 38 individual stars, as well as an estimation of their membership probability \( P_i \). The latter, obtained using an expectation maximization algorithm (Walker et al. 2009), quantifies the probability that a given star belongs to the dSph or to the Milky Way foreground.

The top panel of Figure 2 presents the velocity dispersion profile of Ret II, as well as its reconstruction with the Jeans analysis.\(^9\) The bottom panel of Figure 2 shows the distribution of membership probabilities as a function of the projected radius \( R \) and the departure from the mean velocity (color-coded), for stars with non-zero \( P_i \). As pointed out in Bonnivard et al. (2015a), a large fraction of stars with both intermediate \( P_i \) (0.05 < \( P_i < 0.95 \)) and large departure from the mean velocity.
Figure 1. Projected stellar density profile of Ret II, derived from the photometric catalog of Koposov et al. (2015a). Overplotted (red line) is the best-fitting model (we note that the fit is to the unbinned data), which is the sum of contributions from Ret II itself and a constant background (see Section 2.3). Dotted lines enclose 68% CIs for the projection of $\nu(r)$.

Figure 2. Top: velocity dispersion profile of Ret II and reconstructed median and credible intervals (solid and dashed black lines, respectively), as well as best fit (see footnote 9; long dashed red lines). Bottom: distribution of membership probabilities as a function of the projected radius $R$ and the departure from the mean velocity ($z$-axis, blue to red color) for the eighteen stars with $P_i = 0$. The size of the points is proportional to the velocity uncertainty. See text for discussion.

Table 1

| $\alpha_{int}$ (deg) | $\log_{10}(J(\alpha_{int}))$ ($J/\text{GeVcm}^{-2}$) | $\log_{10}(D(\alpha_{int}))$ ($D/\text{GeVcm}^{-2}$) |
|---------------------|---------------------------------|---------------------------------|
| 0.01                | $17.1_{-0.8}^{+0.5}(0.9)$       | $15.7_{-0.3}^{+0.6}(1.0)$       |
| 0.05                | $18.3_{-0.6}^{+0.5}(0.9)$       | $17.0_{-0.3}^{+0.5}(1.0)$       |
| 0.1                 | $18.8_{-0.5}^{+0.4}(0.9)$       | $17.6_{-0.3}^{+0.5}(1.0)$       |
| 0.5                 | $19.6_{-0.5}^{+0.4}(0.9)$       | $18.8_{-0.3}^{+0.5}(1.0)$       |
| 1                   | $19.8_{-0.5}^{+0.4}(0.9)$       | $19.3_{-0.3}^{+0.5}(1.0)$       |

Notes. For five different integration angles, the median $J$ (resp. $D$)-factors as well as their 68% and 95% CIs are given. Note that possible triaxiality of the dSph galaxies adds a systematic uncertainty of $\pm 0.4$ (resp. $\pm 0.3$) (Bonnivard et al. 2015b) and is not included in the quoted intervals.

$^a$ $1 \text{ GeV}^2 \text{ cm}^{-2} = 2.25 \times 10^{-7} \text{M}_\odot^2 \text{kpc}^{-2}$.

$^b$ $1 \text{ GeVcm}^{-2} = 8.55 \times 10^{-13} \text{M}_\odot \text{kpc}^{-2}$.

Walker et al. 2015 after exclusion of Ret2-142 as our fiducial setup.

3. RESULTS

Figure 3 displays the $J$- (top) and $D$-factors (bottom) of Ret II, reconstructed from the Jeans/MCMC analysis, as a function of the integration angle $\alpha_{int}$. Solid lines represent the median $J$- and $D$-factors as well as their 68% and 95% CIs, respectively. Our data-driven Jeans analysis gives large statistical uncertainties due to the small size of the kinematic sample, comparable to those obtained for other “ultrafaint” dSphs by Bonnivard et al. (2015a; see also Figure 4). Table 1 summarizes our results for the astrophysical factors of Ret II.

We cross-check our findings by varying different ingredients of the Jeans analysis. The resulting $J$-factors are shown in Figure 4. First, we perform a binned Jeans analysis (see Bonnivard et al. 2015a) of the kinematic data, and find...
Figure 4. Comparison of the J-factors at $\alpha_{\text{int}} = 0.5^\circ$ obtained for Ret II (red circle) and for the potentially brightest objects from Bonnivard et al. (2015a) (blue squares), with the same Jeans/MCMC analysis. Ret II is comparable to Wil I in terms of J-factors, but slightly below Coma and UMa II. A 0.4 dex systematic uncertainty was added in quadrature to the 68% CIs to account for possible triaxiality of the DM halo (Bonnivard et al. 2015b). Also shown are the J-factors obtained for Ret II by varying different ingredients of the analysis—see Section 3.

4. COMPARISON TO OTHER dSphs

The same Jeans analysis has been applied to 21 other dSphs in Bonnivard et al. (2015a). In Figure 4, we compare the J-factors (for $\alpha_{\text{int}} = 0.5^\circ$) of Ret II to the brightest objects identified in Bonnivard et al. (2015a). Ret II is comparable to Wilman I in terms of its median J-factor, but slightly below Coma Berenices and Ursa Major II. Its CIs are typical of an "ultrafaint" dSph, and significantly larger than the uncertainties of "classical" dSphs.

Interpreting the possible $\gamma$-ray signal in Ret II in terms of DM annihilation (Geringer-Sameth et al. 2015b; Hooper & Linden 2015), one would expect similar emissions from the dSphs with comparable J-factors, such as UMa II, Coma, and Wil I. However, no excess was reported from these latter objects (Geringer-Sameth et al. 2014; Fermi-LAT Collaboration 2015). This could be explained by the large statistical and systematic uncertainties in the J-factors. Moreover, the Jeans analysis assumes all of these objects to be in dynamical equilibrium, but tidal interactions with the Milky Way could artificially inflate the velocity dispersion and therefore the astrophysical factors. UMa II, and to a lesser extent Coma, appear to be experiencing tidal disturbance (Simon & Geha 2007; Fellhauer et al. 2007; Munoz et al. 2010; Smith et al. 2013), while Wil I may show non-equilibrium kinematics (Willman et al. 2011). Caution is therefore always advised when interpreting the astrophysical factors of these objects. The dynamical status of Ret II is not yet clear. Its flattened morphology may signal ongoing tidal disruption. However, the available kinematic data do not exhibit a significant velocity gradient that might be associated with tidal streaming motions (Walker et al. 2015).

5. CONCLUSION

We have applied a spherical Jeans analysis to the newly discovered dSph Ret II, using 16 likely members from the kinematic data set of Walker et al. (2015). We employed the optimized setup of Bonnivard et al. (2015a, 2015b), which was found to mitigate several biases of the analysis, and checked that our results are robust against several of its ingredients. We find that Ret II presents one of the largest annihilation J-factors among the Milky Way’s dSphs, possibly making it one of the best targets to constrain DM particle properties. However, it is important to obtain follow-up photometric and spectroscopic data in order to test the assumptions of dynamical equilibrium as well as to constrain the fraction of binary stars in the kinematic sample. Nevertheless, the proximity of Ret II and its apparently large DM content place it among the most attractive targets for DM particle searches.

This work has been supported by the “Investissements d’avenir, Labex ENIGMASS,” and by the French ANR, Project DMAstro-LHC, ANR-12-BS05-0006. M.G.W. is supported by National Science Foundation grants AST-1313045, AST-1412999. S.M.K. is supported by DOE DE-SC0010010, NSF PHY-1417505, and NASA NNX13AO94G. M.M. is supported by NSF grants AST-0808043 and AST-1312997. E.W.O. is supported by NSF grant AST-0807498 and AST-1313006.

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10 The best-fit DM profile and anisotropy parameters for each sample are obtained by maximizing the likelihood of Equation (4). J-factors were then computed for these best fitting profiles.

11 Segue I may have a highly uncertain J-factor (V. Bonnivard et al. 2015, in preparation). We show it only for illustration purposes.

12 The latter comes from a possible triaxiality of the dSph (0.4 and 0.3 dex for annihilation and decay respectively, see Bonnivard et al. 2015b), and depends on the LOS orientation with respect to the principle axes of the halo.
