Effects of the Sagittarius Dwarf Tidal Stream on Dark Matter Detectors

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The Sagittarius dwarf tidal stream may be showering dark matter onto the solar neighborhood, which can change the results and interpretation of direct detection searches for weakly interacting massive particles (WIMPs). Stars in the stream may already have been detected in the solar neighborhood, and the dark matter in the stream is (0.3–25)% of the local density. Experiments should see an annually modulated steplike feature in the energy recoil spectrum that would be a smoking gun for WIMP detection. The total count rate in detectors is not a cosine curve in time and peaks at a different time of year than the standard case.

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Dark matter in the halo of our galaxy may consist of WIMPs (weakly interacting massive particles). More than 20 collaborations worldwide are developing detectors designed to search for WIMPs through their elastic scattering off nuclei. The most frequently assumed velocity distribution for galactic dark matter is that of a simple isothermal sphere. However, recent observations of the stellar component of the galactic halo show evidence of a merger history that has not yet become well mixed and indicate that halos form hierarchically. The Sloan digital sky survey and the two micron all sky survey [1,2] have traced the tidal stream [3] of the Sagittarius dwarf galaxy (Sgr), a satellite galaxy that is located inside the Milky Way. Two streams of matter are being tidally pulled away from the main body of the Sgr galaxy and extend outward from it. The leading tail is showering matter down upon the solar neighborhood [2]. Here we show the effect of this stream on WIMP dark matter direct detection experiments. Further details can be found in our longer paper [4].

Estimates of the current mass-to-light ratio of the Sgr dwarf (and hence plausibly the tidal tails) are $M/L \sim (25–100)$ [2,5]. We estimate a range for the local stream dark matter density [4]: $\rho_{\rm str} = [2, 190] \times 10^4 M_\odot/{\rm kpc}^3 = [0.001, 0.07]\ {\rm GeV/cm}^3$, which corresponds to (0.3–25)% of the local density of the isothermal galactic halo, assuming $\rho_h = 0.3\ {\rm GeV/cm}^3$ [6]. At the solar position, we expect the tidal stream to travel roughly orthogonal to the galactic plane with a speed of ~300 km/s. We suggest an identification of the Sgr stream with a previously discovered [8] coherently moving group of stars. Other (lower density) tidal streams may pass by the solar neighborhood, too.

The additional WIMP flux from the Sgr stream gives a 0.3%–25% increase in the count rate in detectors at energies below a characteristic energy E_c, the highest energy that stream WIMPs can impart to a target nucleus. Thus, as pointed out by Refs. [7,9] for generic WIMP streams, we predict a steplike feature in the energy recoil spectrum.

The count rate in WIMP detectors will experience an annual modulation of amplitude ~10% due to Earth's motion around the Sun [10,11]. For an isothermal halo, the peak count rate is on June 2. The count rate of the Sgr stream is also annually modulated, with a peak date different from that of the halo. Hence, as pointed out by Refs. [7,9] for generic streams, the total signal (from halo plus stream) has a modified time dependence and peak date. The step energy E_c is also annually modulated; detection of this modulation would provide powerful confirmation of a WIMP stream signal. For WIMP masses heavier than 50 GeV, the step lies above the threshold energy of current and upcoming dark matter experiments and would affect their results. If their signal is due to WIMPs, DAMA [12] should have the stream in their current data.

Local stars in the Sagittarius tidal tails.—Seven of 97 stars (7%) identified as halo stars by Helmi *et al.* [8], within 1 kpc of the Sun, are moving coherently in one direction. Recently, Majewski *et al.* [2] noticed that the density of this clump of giant stars in the solar region is similar to the expected local density of stars from the Sgr dwarf tidal stream. However, the Y component of the stars' velocity is too high to be consistent with the Sgr dwarf orbital plane. The velocity vector of these stars is 15° away from the orbital plane of the Sgr dwarf spheroidal galaxy, as measured by the positions of the stars in the tidal tails, consistent with a plane that is tipped further from the galactic pole.

In order to determine their velocity components, we reextracted eight clump stars from Chiba and Yoshii [13]. We confirmed Helmi *et al.*'s velocity of 290 ± 26 km/s and found that the direction of the stars' motion is $(l, b) = (116, -59)$. In galactic coordinates [14], the mean velocity of the local stellar clump is $(V_X, V_Y, V_Z) = (-65 \pm 22, 135 \pm 12, -249 \pm 6)$, with velocity dispersions $(\sigma_{V_X}, \sigma_{V_Y}, \sigma_{V_Z}) = (62, 33, 17)$ km/s. Our measurement of the dispersion in the X direction is significantly smaller than previously measured [8]. Since the experimental errors in the space velocities of these stars are of the order of 10 km/s in each component, the asymmetric velocity dispersions are likely to be inherent to this kinematic component and not a result of measurement error.

Except for the fact that the Helmi *et al.* stars are in a less polar orbit than the Sgr dwarf, the characteristics are as expected for the stars associated with the Sgr dwarf spheroidal galaxy. They are a spatially distinct component (surveying larger volumes does not produce a star count that increases linearly with the volume) [15]. They have very nearly the predicted speed [4] and expected stellar density [2]. They are the most significant low-velocity-dispersion component at the solar position.

Given the large number of coincidences with our expectations for Sgr stream stars, it is logical to revisit whether a velocity direction that differs from the Sgr orbital plane by 15° rules out an association. The Y component of the Helmi *et al.* stars is 5σ higher than that required to match the published Sgr plane. However, it is conceivable that the Sgr stream properties in the solar neighborhood deviate from the Sgr dwarf orbital plane.

In Fig. 5 of Newberg *et al.* [1], it is shown that the known tidal tails of the Sgr dwarf galaxy do not exactly follow the Sgr dwarf orbital plane as fit to M-giants [2]. Fitting a plane to the positions of a piece of the leading tail debris yields a plane that is discrepant by 8° from the nominal orbital plane. In Ref. [4], we estimated a stream width of 6 kpc for a piece of the Sgr tidal tail that was 34 kpc from the galactic center. Though the center of the tidal stream could, in principle, remain in one plane, the individual stars in a stream with this width must differ in orbital plane by 10° or more from one side of the stream to the other. A spatial separation of the velocity components is likely, given that the stars are primarily stripped at the dwarf galaxy's closest approach to the galactic center [16] and are not cast off along the length of the orbit.

Additional contributions to the orbital velocities of stars in a restricted portion of the tidal stream include a nonspherical component of the galactic potential, any halo dark matter "lumps" [17] yet to be discovered, and any rotation of the parent galaxy to the present-day Sgr dwarf spheroidal. All of these unknowns together make it plausible that a local portion of the Sgr tidal stream could have different orbital parameters than naively expected from a global fit to the tidal tails.

Once stripped from the dwarf, stars and dark matter released into the galactic potential at the same position and with the same velocity travel together. The Helmi *et al.* stars provide the most likely velocities for a tidal stream that passes through our location in the Galaxy (though if it is not the Sgr stream, then the dark matter density associated with it is currently unknown). In the remainder of this Letter, we explore the implications of this tidal stream for WIMP direct detection experiments, assuming it has the dark matter density estimated for the Sgr tidal stream.

Count rates.—In WIMP direct detection experiments, the differential detection rate per unit detector mass (counts/day/kg detector/keV recoil energy) is [9]

$$\frac{dR}{dE} = \frac{\sigma_0 F^2(q)}{2m\mu^2}[\rho_h \eta_h(E,t) + \rho_{\rm str}\eta_{\rm str}(E,t)], \qquad (1)$$

where η_h and $\eta_{\rm str}$ are the mean inverse speed of WIMPs in the standard galactic halo and the stream, respectively, m is the WIMP mass, M is the target nucleus mass, $\mu = mM/(m+M)$ is the reduced mass, σ_0 is the total nucleus-WIMP cross section, $q = \sqrt{2ME}$ is the nucleus recoil momentum, and $F(q)$ is a nuclear form factor. More detail can be found in our longer paper [4]. We consider two different sources of WIMPs that contribute to count rates in detectors: WIMPs in the Milky Way halo and WIMPs in the Sgr stream. For the halo WIMPs, we assume an isothermal sphere. The galactic WIMP speeds obey a Maxwellian distribution with a velocity dispersion σ_h truncated at the escape velocity $v_{\rm esc}$. We take $\sigma_h = 270$ km/s and $v_{\rm esc} = 650$ km/s. The resultant rates can be found in Refs. [4,11].

Sgr stream component.—As our reference case, we use a WIMP stream velocity $\mathbf{v}_{\rm str} = (-65, 135, -249)$ km/s. The characteristic energy of the step in the recoil spectrum is

$$E_c(t) = (2\mu^2/M)|\mathbf{v}_{\rm D}(t) - \mathbf{v}_{\rm str}|^2, \qquad (2)$$

where $\mathbf{v}_{\rm D}(t)$ is the detector velocity. This step energy is the maximum recoil energy that can be imparted to the nucleus. The maximum momentum transferred from a WIMP to a nucleus occurs when the WIMP bounces back and is $q_{\rm max} = 2\mu|\mathbf{v}_{\rm D}(t) - \mathbf{v}_{\rm str}|$; the maximum nuclear recoil energy then follows as $E_c(t) = q_{\rm max}^2/(2M)$.

The effect of a velocity dispersion $\sigma_{\rm str}$ in the Sgr stream is to smooth out the edges of the step. We assume that the WIMPs in the Sgr stream follow a Maxwellian velocity distribution $f_{\rm str}(\mathbf{v}) = (2\pi\sigma_{\rm str}^2/3)^{-3/2} e^{-3|\mathbf{v}-\mathbf{v}_{\rm str}|^2/2\sigma_{\rm str}^2}$. We use $\sigma_{\rm str} = 72$ km/s but will study the effects of an anisotropic $\sigma_{\rm str}$ in a later paper.

Sgr stream annual modulation.—The position of the step depends on the time of year:

$$E_c(t) = E_c^{(0)}\{1 + A_c \cos[\omega(t - t_c)]\}, \qquad (3)$$

with $\omega = 2\pi/1$ yr, and $E_c^{(0)}$ and A_c given in Ref. [4]. For the Sgr stream, we find that the amplitude of the annual modulation of the step energy is $A_c = 25.2\%$. The location of the step is at the highest energy $E_{c,\rm max}$ on January 15 and lowest energy $E_{c,\rm min}$ on July 16. The amplitude and phase of the E_c modulation do not depend on the target nucleus, WIMP mass, or density of stream WIMPs, but do depend on the size and direction of the stream velocity.

The count rates from both the halo and stream WIMPs also experience annual modulation. Since the halo and stream count rates peak on different days of the year, the peak date of the total signal depends on the fractional stream contribution. The peak date of the stream contribution depends on the stream direction and the recoil energy. For our reference direction, at recoil energies below $E_{c,\min}$, the stream count rate (dominated at low recoil energies by slow WIMPs relative to the Earth) peaks on July 16 and is minimum on January 15. Above $E_{c,\min}$, fast stream WIMPs (relative to the Earth) dominate the stream count rate, and the phase of the annual modulation reverses: the stream count rate peaks on January 15 and is minimum on July 16. For recoil energies above $E_{c,\max}$, the stream disappears entirely, and one returns to the annual modulation of the halo, with a peak on June 2. The phase of the modulation of E_c is 180° out of phase with the stream modulation below $E_{c,\min}$ and in phase with the stream modulation between $E_{c,\min}$ and $E_{c,\max}$ (above which the stream signal disappears).

At a given energy recoil, the total observed signal can have a variety of periodicities that do not resemble sinusoids over the course of a year. For example, the peak of the stream signal on January 15 can produce a bump in the time series of the total signal. Since the stream peak depends sensitively on the direction of the stream, the total count rate of halo plus stream can vary widely, depending on the stream contribution. In particular, the peak date of the total observable signal can vary over the entire year, depending on the stream contribution. Any stream component can thus drastically affect what experimenters will find.

Results.—As an illustrative example, we focus here on the NaI detector of the DAMA experiment. We assume $\sigma_0 = 7.2 \times 10^{-42}\ \mathrm{cm}^2(\mu/\mu_p)^2A^2$, where A is the atomic mass and μ_p is the reduced WIMP-proton mass. As discussed in Ref. [4], the stream should be visible in other experiments as well.

DAMA has an energy threshold of 2 keV electron equivalent (keVee), which corresponds to 22 keV recoil energy for iodine [18]. In Table I, we list the values of the step energy E_c due to Sgr stream WIMPs for our reference case [19]. E_c experiences an annual modulation, with a maximum in January and a minimum in July. Since iodine is much heavier than sodium, WIMP interactions with iodine dominate the count rate (except for a high energy tail above E_c of iodine). For WIMP masses heavier than 50 GeV, the step lies above the DAMA threshold energy during peak months and can, in principle, be detected.

TABLE I. Step energy E_c in keVee from WIMPs in the Sgr stream for Na and I on maximum and minimum dates, January 15 and July 16, for our reference case.

Target	$m = 60$ GeV		$m = 100$ GeV		$m = 500$ GeV	
Nucleus	$E_{c,\min}$	$E_{c,\max}$	$E_{c,\min}$	$E_{c,\max}$	$E_{c,\min}$	$E_{c,\max}$
^{127}I	1.87	2.50	3.47	4.64	10.8	14.5
^{23}Na	5.43	7.26	6.79	9.08	9.22	12.3

Figure 1 shows the time series of the count rate of 60 GeV WIMPs in the detector, integrated over the 2–6 keVee energy bin for which DAMA published results. For a 4% stream contribution, the count rate of the halo alone peaks on June 2, the stream alone on January 15, and the sum of the two on May 25. The DAMA experiment finds that the count rate in their data peaks on May 21 ±22 days (1σ error bars [12]). The error band includes June 2 (predicted by an isothermal halo model) but is better fit by the presence of the stream. The peak date of the total count rate (including stream) is extremely sensitive to the direction and density of the stream. For 60 GeV WIMPs and a 20% stream contribution, the peak date of the total signal in the 2–6 keVee bin is March 30, in disagreement with the data. Thus, DAMA cannot be seeing a stream with these parameters.

Figure 2 shows the count rate of 60 GeV WIMPs in a NaI detector such as DAMA as a function of recoil energy. A stream WIMP fraction of 20% is depicted to illustrate the step, though a 4% WIMP fraction is more likely. The DAMA experiment has an enormous exposure of 107 731 kg days. For a 60 GeV WIMP mass and a Sgr stream in the reference direction that is 4% of the local halo density, we compute the following number of events expected in the (2–3, 3–4) keVee bins, averaged over a year: (112 372, 50 894) with the stream and (108 544, 50 425) without the stream (assuming a detector resolution much smaller than the bin size). The location of $E_{c,\max}$ due to iodine is 2.5 keVee. Thus, the stream is detectable at the 11σ level $[(112\,372 - 108\,544)/\sqrt{112\,372} = 11\sigma]$ in the 2–3 keVee bin and at the 2σ level in the 3–4 keVee bin. For higher masses, the value

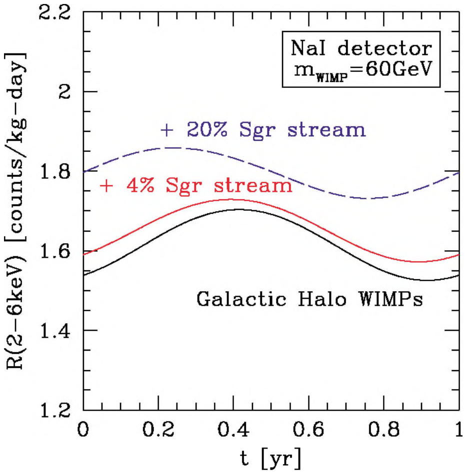

FIG. 1 (color online). Count rate of 60 GeV WIMPs over the course of a year in a NaI detector such as DAMA due to the halo alone as well as the sum of the halo and stream, for our reference direction for stream densities that are 4% and 20% of the halo, and in the 2–6 keVee bin.

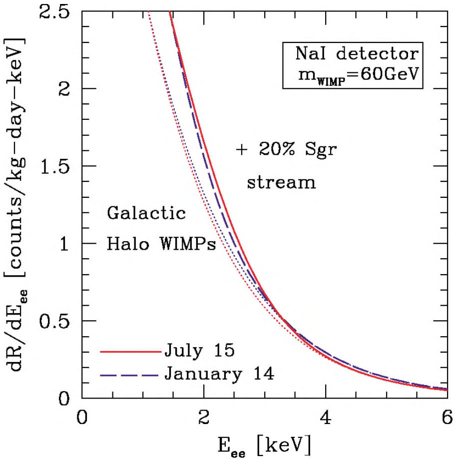

FIG. 2 (color online). Count rate of 60 GeV WIMPs in a NaI detector such as DAMA vs recoil energy. The dotted lines show the count rate from galactic (isothermal) halo WIMPs alone. The solid and dashed lines show the step in the count rate if we include the Sgr stream WIMPS. The plot assumes that the stream contributes an additional 20% of the local galactic halo density and comes from our reference direction. The solid and dashed lines are for July 15 and January 14, respectively, the dates of maximum and minimum count rate for the stream.

of E_c is larger so that stream WIMPs contribute out to higher energy recoils. Stream WIMPs with higher mass are detectable in the first few energy bins, even for rather low dark matter densities in the stream. For example, for 70 GeV WIMPs, a 4% stream is detectable at the 16σ level in the 2–3 keVee bin and at the 5σ level in the 3–4 keVee bin. For 85 GeV WIMPs, even a 2% (1%) stream is detectable at the 9σ (5σ) level in the 2–3 keVee bin and at the 5σ (3σ) level in the 3–4 keVee bin.

Experiments may be able to see the annual modulation of the step, which is important to proving that they have indeed seen the Sgr stream. With the current DAMA energy resolution of 7.5%, DAMA may be able to make this identification in some cases but not in others. For the reference case, the energy resolution is better than the difference in E_c due to annual modulation (for those cases where E_c is above threshold). Finding the Sgr modulation would be persuasive in the interpretation of the observed annual modulation in DAMA as indeed due to WIMPs.

Conclusions.—Recent observations of the Sgr dwarf spheroidal galaxy indicate the existence of tidal streams that pass through the solar neighborhood. It is possible that stars associated with the stream have already been detected in the solar neighborhood [8]. If dark matter consists of WIMPs, the extra contribution from the stream gives rise to a steplike feature in the energy recoil spectrum in direct dark matter detection. The location of the step experiences an annual modulation that will be useful in identifying the existence of the stream. The count rate in the detector due to stream WIMPs is also modulated annually. With our best estimates, the maximum is on January 15 and the minimum on July 16 for energy recoils near the characteristic energy; for lower energy recoils, the phase is opposite.

For current and upcoming experiments, the step may lie above the threshold energy and can be detected. DAMA may have it in their current data. For a 60 GeV WIMP mass and a very reasonable stream density that is 4% of the local halo, the stream is detectable at the 11σ level in the 2–3 keVee energy bin; then the total count rate peaks on May 25, in excellent agreement with the data. The existence of the Sgr stream in the DAMA data may shift the best fit WIMP mass and cross section [20]. It is possible that the discrepancy between DAMA and EDELWEISS, CDMS, or ZEPLIN-I data may be resolved if the stream is correctly included. We also note that other experiments, e.g., CDMS, CRESST, DRIFT, ZEPLIN, and XENON, should also be able to see the stream, as discussed in our longer paper [4].

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[20] Since the DAMA data are not public, we are compelled to leave the analysis to the experimentalists.