A Model-Independent Radio Telescope Dark Matter Search

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Abstract. A novel search technique for ultralight dark matter has been developed and initially carried out over a limited range of frequency in L-band, utilizing the recent Breakthrough Listen public data release of three years of observation with the Green Bank Telescope. The search concept depends only on the assumption of decay or annihilation of virialized dark matter leading to a quasi-monochromatic radio line, and additionally that the frequency and intensity of the line be consistent with very general expected properties of the phase space of our Milky Way halo. Specifically, the search selects for a line which exhibits a Doppler shift with position according to the solar motion through a static galactic halo, and similarly varies in intensity with position with respect to the halo profile. The analysis of the full L-, S-, C- and X-band dataset by this method is currently underway.

1. Introduction
While the existence of dark matter has been put on a firm foundation already for several decades, limited progress has been made regarding its identification. Axion searches, while finally possessing meaningful sensitivity within one decade of mass [1], now face theoretical mass bounds which have been relaxed by several orders of magnitude. Furthermore, a much broader theoretical framework for dark matter has emerged, allowing $10^{-22} - 10^{-2} \text{ eV}$ in mass [2]. This represents a daunting challenge, for which the broadened scope of dark matter theory calls for a similarly broadened approach in astrophysical observation, in the hope of gleaning useful clues for the ultimate detection of dark matter. An optimal observational and analysis strategy should thus rely on as few general and robust assumptions as possible, while possessing a high degree of selectivity and sensitivity to dark matter.

2. General Concepts
This search focuses on the possible radiative decay or annihilation of ultralight dark matter within our Milky Way galactic halo, leading to a quasi-monochromatic radio line ($\delta \nu / \nu \approx 10^{-3}$). This search is predicated on two generally accepted characteristics of dark matter in our galactic halo. First, we assume that the dark matter constitutes a static halo through which our solar system is moving, with a characteristic velocity $v_S \approx 230 \text{ km/s}$ tangential to our galactic disk. Consequently, such a radio line would be distinguished from any other source, conventional or otherwise, by a systematic Doppler shift with respect to the sun's direction of motion $(l,b) = (90^\circ,0^\circ)$. Second, the signal should reflect the spatial distribution as represented by a standard halo model; the signal should follow the line-integrated density of the halo $\rho$ for dark-matter decay or $\rho^2$ for annihilation.

Dark matter decay here includes all processes $\chi \to \phi + \gamma$, including in principle two-photon decays from e.g. a pseudoscalar such as the axion or an axion-like particle $\chi \to \gamma + \gamma$, and for simplicity in
calculating and presenting limits on the decay rate, $\lambda$, we will assume the photon energy $h\nu = \frac{m_\chi}{2}$. What we refer to as annihilation similarly subsumes all two-body initial states, including annihilation proper $\chi + \chi \rightarrow \phi + \gamma$ as well as Compton-like processes $\chi + \xi \rightarrow \phi + \gamma$, where $\xi$ and $\phi$ represent any standard model or beyond-standard model particles; see Figure 1.

3. The Breakthrough Listen (BL) data set

This analysis utilizes the Breakthrough Listen (BL) public data release from the 100-m Robert C. Byrd Green Bank Telescope (GBT), taken between January 2016 and March 2019 [3]. The BL program to date has focused on $\approx 1700$ nearby Hipparcos catalog stars and 100 nearby galaxies; observations with the GBT have been taken with receivers covering L-, S-, C- and X-band (1.1-11.6 GHz). The raw spectra used in this analysis have an intrinsic channel resolution of $\approx 2.8610$ kHz, and are imprinted with the polyphase filterbank structure, a symmetric bandpass function repeated every 1024 channels. Clearly, the uniqueness of the BL data set for a general dark matter search is the total integration time it represents, democratically covering the galaxy accessible to the GBT.

4. Analysis

This approach differs from similar dark matter searches insofar as it is not restricted to specific particle candidates nor to specific astrophysical sites, but is model-independent and utilizes the entire BL data set comprehensively covering the Milky Way. The cases of dark matter decay and annihilation are treated separately, as their observed line widths differ. Assuming a static halo of uniform virial velocity, the Doppler broadening of the source along the line of sight for the two cases is given by

$$\sigma_D \nu = \frac{\sigma_V}{\sqrt{3}c} \quad \text{and} \quad \sigma_A \nu = \frac{\sigma_V}{\sqrt{6}c}$$

(1)

where $\sigma_D$ and $\sigma_A$ denote the standard deviation in frequency associated with decay and annihilation respectively, and $\sigma_V$ the virial velocity of the halo. For a virial velocity of 250 km/sec, $\frac{\Delta \nu}{\nu} \approx 5.2 \times 10^{-4}/3.7 \times 10^{-4}$ for decay and annihilation respectively, corresponding to 0.91/0.64 MHz at 1.75 GHz.

For each frequency band, this analysis requires the combining of thousands of spectra taken over a year or more, at differing times of day, sky position, atmospheric conditions, hardware and software configurations, etc. Thus, after dividing the raw data by the polyphase filter function (PPF) and excising 48 points at the beginning and end of each of the repeated 1024-channel bandpass response, the spectra are unit normalized. This is done by forming a ratio of moving polynomials fit to the PPF-corrected spectrum within a window around each data point in the spectrum.

The polynomial in the denominator is weighted by a Gaussian:

$$W(\nu, \nu_i) = 1 - a \cdot \exp\left[\frac{-(\nu - \nu_i)^2}{2b^2\sigma_{A,D}^2(\nu_i)}\right]$$

(2)

For the unweighted polynomial in the numerator, the fit more closely tracks any signal atop the local background, whereas the weighted (or more precisely de-weighted) polynomial is desensitized to any putative signal around $\nu_i$, and thus more closely interpolates the real background in the absence of such a signal. The variables $a$ and $b$ were chosen in order to maximize the signal-to-noise ratio. An example normalization is shown in Figure 2.
Figure 2: (a) A synthetic signal from dark matter annihilation with velocity weighted cross section \( <\sigma v> = 1.0 \times 10^{-42} \text{cm}^3\text{s}^{-1} \) injected into the raw data of one spectrum, with the corresponding weighted and unweighted polynomial fits. (b) The resulting normalized spectra for the cases with and without the injected signal.

The concept of the Doppler and intensity asymmetries is schematically represented in Figure 3. In the case of the Doppler asymmetry, under the assumption of a static halo, an actual signal will be Doppler shifted according to its polar angle \( \theta \) from the direction of the sun’s motion through the galaxy:

\[
\nu' = \nu \left(1 + \frac{V_S}{c} \cos \theta \right)
\]  

(3)

For each case, the asymmetry spectrum is formed:

\[
A_D(\nu) = \frac{F - B}{F + B}, \quad A_I(\nu) = \frac{I - O}{I + O}
\]

(4)

with \( F \) (B) designating the average of all spectra within the Forward (Backward) acceptances defined by their polar angles \( \theta_{F/B} \):

\[
F(\nu) = \frac{1}{n_f} \sum \nu_i f_i(\nu), \quad B(\nu) = \frac{1}{n_b} \sum \nu_i b_i(\nu)
\]

(5)

and similarly for I (O), the Inward (Outward) populations within their respective polar angle cuts \( \Phi_{I/O} \). Forming asymmetry spectra has the virtue of cancelling out to a high degree common-mode residual structure apparent in all normalized spectra at the \( \approx 10^{-4} \) level, thus enabling a more sensitive search.

Figure 3: Concept of asymmetry-based searches for dark matter within a large data set.
4.1. Doppler asymmetry analysis

The flux density in general for the two cases of annihilation and decay processes is given by:

\[
P_A \Delta A \Delta \nu = \sqrt{\frac{\pi}{8192}} \frac{\langle \sigma v \rangle}{M_\chi} \eta A \nu_0 (\Delta \theta)^2 \exp\left[-\frac{(\nu - \nu_0)^2}{2 \eta^2 \nu_0}\right] \int_0^\infty \rho(\vec{r})^2 d\vec{r}
\]

(6)

\[
P_D \Delta A \Delta \nu = \frac{\lambda}{8192} \frac{\eta D \nu_0}{\nu_0} (\Delta \theta)^2 \exp\left[-\frac{(\nu - \nu_0)^2}{2 \eta^2 D \nu_0}\right] \int_0^\infty \rho(\vec{r})^2 d\vec{r}
\]

(7)

which depends on the velocity-weighted cross section \(\langle \sigma v \rangle\) for annihilation, or the decay constant \(\lambda\) in the case of decay. Here \(\eta\) is the line width, \(\sigma\) is the halo viral velocity, \(\rho(\vec{r})\) is the halo density along the line of sight, and \(\Delta \theta\) is the frequency-dependent FWHM beam width of the telescope.

For the development and demonstration of this analysis, we selected a limited range of the BL L-band data, 1710-1850 MHz. After the normalization of the spectra, a cut was made on the standard deviation to minimize statistical noise and residual structure, yielding \(\approx 4400\) spectra.

The search is carried out and the resulting limits derived by a standard matched-filtering technique. A template of the asymmetry for a dark matter signal is created at each frequency \(\nu\) in the spectrum specific to the particle physics input \(\langle \sigma v \rangle\) or \(\lambda\), target samples \(\theta_{F/B}\), galactic parameters \((V_S, \sigma)\), and halo model. This involves calculating the contribution of the expected signal for each target, transforming the input Gaussian line into the actual shape as it appears in the normalized spectrum, applying the coordinate-dependent Doppler shift, and finally summing and forming the asymmetry. At each frequency \(\nu\) the template is integrated over the asymmetry spectrum resulting in the Doppler correlation spectrum \(R_D(\nu)\).

Limits are derived by injecting synthetic signals at the raw spectrum level, carrying through the analysis as described, and establishing the confidence level against the statistical distribution of \(R_D(\nu)\) in the absence of a signal. The signal-to-noise was maximized by utilizing all of the data after the data quality cut and equalizing the Forward and Backward populations, with \(\theta_F = \theta_B = 65^\circ\).

\[\text{(a)}\]

Figure 4: (a) Doppler asymmetry spectrum for the case \(V_S = 225\) km/sec, \(\sigma = 250\) km/sec, for \(\nu = 1775\) MHz, and a velocity weighted cross section \(\langle \sigma v \rangle = 5.0 \times 10^{-44}\) cm\(^3\) s\(^{-1}\) shown for scale. (Inset) Template formed for current parameters. (b) The Doppler correlation spectrum. (Inset) Doppler correlation spectral distribution in units of standard deviation \(\sigma_{corr}\) in the absence of a signal.

4.2. Intensity asymmetry analysis

The analysis based on the expected signal asymmetry between looking inward (I), toward the galactic center and outward (O), away from the galactic center follows in an essentially identical manner. Here the SNR is maximized by more tightly restricting the cone defining the inward population and leaving a large gap in angle \((\theta_I = 65^\circ, \theta_O = 105^\circ)\).

For the first analysis, a Navarro-Frenk-White (NFW) \([4]\) halo was used:

\[
\rho(\vec{r}) = \rho_c \left(\frac{r}{r_c}\right)^{-1} \left(1 + \frac{r}{r_c}\right)^{-2}
\]

(8)
with $\rho_c = 5.0 \times 10^{-44} M_\odot kpc^{-3}$ and $r_c = 16.1$ kpc [5]. Preliminary explorations indicate that limits vary between halo models (specifically NFW and Burkert, for parameters determined in the same comparative analysis). We foresee that stronger limits could be achieved by cross-correlating the Doppler and intensity analyses, but to do this in the most straightforward way, it is important to make sure that the two analyses are absolutely orthogonal. In particular, it is most important to ensure that there are no remnant velocity correlations inadvertently built in to the I,O populations of the intensity analysis, owing to the incomplete GBT galactic coverage (Figure 3c). To ensure that the total I,O contributions are coincident in frequency, that is, free of residual Doppler shift, while maximizing the number of spectra selected (here 1581), the Hungarian matching algorithm was used [6].

Figure 5: (a) Intensity asymmetry spectrum. (b) Intensity correlation spectrum and its spectral distribution, for the same case as in Figure 4.

The projected limits (97.5% c.l.) for each analysis (Doppler and Intensity) are approximately $<\sigma v> = 2.0 \times 10^{-44} cm^3 s^{-1}$ for annihilation and $\lambda = 5.0 \times 10^{-34} s^{-1}$ for decay with $(V_S, \sigma) = (225, 250)$ [km/s].

In addition to the improvement from cross-correlating the analyses, the limits will further be strengthened by considering stimulated emission in the presence of the CMB and Galactic diffuse emission [7].

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