A SEARCH FOR STELLAR OBSCURATION EVENTS DUE TO DARK CLOUDS

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ABSTRACT

The recent detections of a large population of faint submillimeter sources, an excess halo γ-ray background, and the extreme scattering events observed for extragalactic radio sources have been explained as being due to baryonic dark matter in the form of small, dark gas clouds. In this paper, we present the results of a search for the transient stellar obscurations such clouds are expected to cause. We examine the MACHO project light curves of $48 \times 10^6$ stars toward the Galactic bulge, Large Magellanic Cloud, and Small Magellanic Cloud for the presence of dark cloud extinction events. We find no evidence for a population of dark gas clouds with $A_V > 0.2$ in the masses range from $\sim 10^{-4}$ to $2 \times 10^{-2} M_\odot$, in either the Galactic disk or halo. However, it is possible that such dark cloud populations could exist if they are clustered in regions away from the observed lines of sight.

Subject headings: dark matter — dust, extinction — Galaxy: halo — ISM: clouds
On-line material: color figures

1. INTRODUCTION

It has been proposed that a large fraction of the baryonic dark matter in the halo of our Galaxy could be in the form of cold, dense gas clouds (de Paolis et al. 1995; Gerhard & Silk 1996). Such clouds would be extremely difficult to detect directly with traditional means due to their dark nature. However, the extreme scattering events observed by Fiedler (1987) have been given as evidence for AU-sized, planetary-mass gas clouds (Henriksen & Widrow 1995; Walker & Wardle 1998). Further evidence for the existence of such clouds comes from the detections of large populations of faint submillimeter sources detected by SCUBA (Submillimeter Common User Bolometric Array; Lawrence 2001). Yet more evidence for such a population comes from recent EGRET (Energetic Gamma Ray Explorer Telescope) results that show the presence of a background γ-ray emission from the Galactic halo. Kalberla, Schekinov, & Dettmar (1999) have suggested that these results can be explained as due to the interaction of high-energy cosmic rays with dense H\textsubscript{2} clumps with masses $\sim 10^{-3} M_\odot$, and radii $\sim$6 AU. These detections and prior observational and dynamical arguments have led to further suggestions about how a halo dark cloud population could be discovered (Kerins, Binney, & Silk 2002, hereafter KBS; Kamaya & Silk 2002). Although most models place the cloud population within the halo, Pfenniger & Combes (1994) suggested that such clouds are a natural part of the cold interstellar medium (ISM) and would exist concomitant with the thin H\textsubscript{i} disk.

For dark clouds to have survived until the present day, they must have a mass that is sustainable over a Hubble time. Within the Galaxy, the lower mass limit is $10^{-6} M_\odot$ because smaller masses will evaporate due to cosmic-ray heating (Wardle & Walker 1999). It is also expected that these objects will contain some metals since it has been suggested that clouds with primordial composition cannot cool below 100 K (Murray & Lin 1990). Any population of gas clouds must be much cooler than this to have escaped detection in previous surveys (Lawrence 2001). The presence of a small amount of metals can assist the cooling of gas clouds (Gerhard & Silk 1996). It has been suggested that even if the clouds were dust-free, they could be stabilized against gravitational collapse by cosmic-ray heating (Sciamma 2000). However, SCUBA sources exhibit continuous emission in the submillimeter band, which may be due to dust (Lawrence 2001). The SCUBA results led to likely cloud masses of $10^{-4} - (2 \times 10^{-2}) M_\odot$ with temperatures less than 18 K. The virial radius of a cloud with $T = 18$ K and $M = 10^{-4} M_\odot$ is 0.39 AU, and for a cloud with $T = 10$ K and $M = 10^{-2} M_\odot$, the virial radius is 70 AU. These radii set likely limits on the sizes of a gas cloud population. Further limits on clouds sizes and masses come from constraints on gaseous lensing events. Raficov & Draine (2001) note that no gaseous lensing events have been observed toward the Large Magellanic Cloud (LMC) by the MACHO project, while many events are expected for a significant population of compact gas clouds. Massive compact objects such as clouds, stars, or other objects will lens stars as they pass through our line of sight of the stars. Since lensing is not observed, any clouds present must exceed the projected Einstein radius. The analysis of Raficov & Draine (2001) suggests that cloud must have radii from 2 to 300 AU for cloud masses between $M = 10^{-4}$ and $2 \times 10^{-2} M_\odot$ for temperatures of 10–100 K. Another constraint on the dark clouds comes from the EGRET results of Kalberla et al. (1999). They find that the γ-ray results are consistent with H\textsubscript{2} clumps with masses $(0.3-3) \times 10^{-3} M_\odot$ and sizes from 3 to 10 AU.

One consequence of the existence of a population of small, dark clouds is the transient obscuration of background stars (Gerhard & Silk 1996). Such events are expected to be very rare, with much less than 1% of stars in any given direction being obscured at any time. However, even a very low rate of obscuration events is detectable with...
the data from microlensing experiments, since millions of stars have been observed for many years (Alcock et al. 2000; Udalski et al. 2000; Derue et al. 2000; Bond et al. 2002). Models for the obscuration event timescale distribution of cloud occultation events have been presented by KBS. They consider two hypothetical cloud populations, one in which the clouds occupy the disk and another where they reside in the halo.

In this paper, we present the results of an analysis of the MACHO light-curve data set to detect light curves consistent with extinction due to passing dark clouds. We will search for events toward stars in the disk (Galactic bulge) and the halo (LMC and SMC, or Small Magellanic Cloud). To quantify our results, we determine our detection efficiency for the various possible dark cloud parameters in the KBS models.

2. OBSERVATIONS

The MACHO project repeatedly imaged ~67 million stars in a total of 182 observation fields toward the Galactic bulge, the LMC, and the SMC to detect the phenomenon of microlensing (Alcock et al. 1997). The data were taken in ~90,000 individual observations, each covering a total area of 43° × 43° on the sky. When field overlap is considered, the 182 fields observed cover approximately 80 deg². These images were taken between 1992 and 2000 on the Mount Stromlo and Siding Springs Observatories’ 1.3 m Great Melbourne Telescope with the 8 × 2048² pixel dual-color wide-field MACHO camera. Observations toward the Galactic bulge have exposure times of 150 s, while toward the LMC and the SMC, they have 300 and 600 s exposure times, respectively. The photometry was carried out using a fixed position point-spread function (PSF) photometry package derivative of the DoPhot package (Schecter, Mateo, & Saha 1993) called SoDOPHOT (Bennett 1993). The images were taken with nonstandard $B_M$ and $R_M$ bands and can be converted to the standard Kron-Cousins system $V$ and $R$ using the photometric calibrations given in Alcock et al. (1999). The data set provides a consistent set of photometry for stars spanning the duration of the experiment.

The observations toward the LMC and the SMC were taken all year round, while the Galactic bulge was observed between March and October. The median seeing of the data set is roughly 2", and measurements reach stars with $V$-band magnitudes between 21 and 22. The photometric sampling frequency varies greatly between the individual fields observed toward the Galactic bulge and the LMC. The least sampled fields have only ~50 observations, while those most sampled have ~2000 observations. For most fields, observations are quite evenly spaced over the experiment’s duration (apart from the observing gaps toward bulge fields). However, a few fields in the LMC and the Galactic bulge have variations in observation frequency because of changes in the observing strategy. Also, a small number of the bulge fields were observed only in the last few years of the project.

To select candidate obscuration events from the MACHO database, we performed a number of cuts to remove data that were noisy or had a low signal-to-noise ratio. We selected stars with magnitudes between 13 < $V$ < 21 toward the Galactic bulge and LMC and 14 < $V$ < 22 for the SMC. For each of the stars in this range, we determined the median magnitude, $M_{10}$, and the standard deviation, $\sigma_{10}$, based on the first 10% of the data points. However, if there were less than 500 observations in a light curve, we used the first 50 data points. We rejected any light curves where $\sigma_{10}$ was larger than 0.7 mag in either passband. All together, these cuts removed ~40% of the stars observed. The parameters of the analyzed data set are given in Table 1.

3. SEARCHING FOR OBSCURATION EVENTS

In this analysis, we aimed to detect stellar occultations due to opaque dust clouds and obscurations due to dark clouds with a small dust-to-gas ratio. We also tried to detect gas cloud transits without restricting the cloud shapes to purely spherical morphology or isotropic dust distribution. Therefore, to find events caused by the passage of dark clouds in front of stars, we were as liberal as possible in our selection of the light curves that might exhibit extinction effects.

First, we selected light curves that exhibited a significant drop in flux that lasted more than 10 days. This selection was required to remove eclipsing binaries and data that were affected by periods of poor observing conditions. Second, we required that the photometry points during the candidate obscuration event were greater than 0.2 mag below the median magnitude and had more than 4 $\sigma$ significance. The uncertainty, $\sigma$, was based on the distribution of the photometry values rather than the individual photometric uncertainties. As the detection of candidate obscuration events is sensitive to the sampling rate of a target field, we also required at least 10 points below the median in any candidate event. To reduce the number of long-period variables detected, we accepted only light curves with less than 50% of the points below $M_{10}$ (the 10% median value). However, we did not require that the flux in a candidate’s light curve return to the median value. In this way, we hoped to retain some of the sensitivity to dark cloud extinction events with timescales longer than the MACHO project’s baseline (~8 yr).

Applying these criteria to the MACHO project photometry data, 5284 (~0.016%) light curves passed our initial selection toward the Galactic bulge, 6427 (~0.050%) toward the LMC, and 678 (~0.027%) toward the SMC. From examination of the candidate’s light curves and their positions in color-magnitude diagrams (CMDs), it was clear that most of the objects passing these selections were long-period variables. This was to be expected since these stars have large variability amplitudes, timescales $\gtrsim$80 days, and red colors. However, we intended to examine the light curves before applying any color selection criteria that might bias our results. As none of the light curves in the
asymptotic giant branch (AGB) region of the CMD appeared consistent with dark cloud transit events, we chose to apply empirical color selections to the candidates toward each target direction. In Figures 1 and 2, we present CMDs of the Galactic bulge, LMC, and SMC stars. The CMDs are composed of ~1000 stars from each of the 182 fields observed. In each figure, we have overplotted the $M_{10}$ magnitudes of the light curves passing our primary selection as obscuration events. We have also plotted the color cuts we applied to remove the AGB variables (to the right of the dashed line) that passed our initial selection criteria. As can be clearly seen, this color selection removes almost all the initial candidates. However, these color cuts remove only ~1% of all stars toward any of the target fields, so they do not significantly change our total exposure. After applying the red variable star cuts, there were 372, 441, and 98 remaining candidates toward the Galactic bulge, LMC, and SMC, respectively. Many of these objects were also clearly variable stars.

Toward the Galactic bulge, many of the candidate events had clump star sources. Almost all of these light curves exhibit sinusoidal modulations superposed on a varying baseline magnitude. The oscillation periods were found to be between 11 and 90 days with amplitudes between 0.02 and 0.2 mag. These stars exhibited baseline magnitude changes of up to ~0.5 mag. All these features are typical of chromospherically active stars (Fekel, Henry, & Eaton 2002) and cannot be explained simply by a transiting dark cloud. Of the candidate events, 155, 10, and 2 light curves (Galactic bulge, LMC, and SMC, respectively) were clearly due to chromospherically active stars and were removed. The variation in the number of objects toward the target fields is due to stellar population differences and the fact that the photometry of clump stars is poorer at the distances of Magellanic cloud stars.

A large number of the candidates in the Magellanic cloud fields were found to be due to the well-known population of bright, blue, Be-variable stars known as bumpers (Keller et al. 2002). These stars occupy a restricted region of the CMD and can show long dips similar to those expected for a cloud transit. However, many also exhibit outbursts similar to dwarf novae. Such flares are not easily explainable in a cloud transit model. We removed an additional 89, 280, and
obscuration event should be well represented by extinction. In this case, the magnitude during an assumed that the detected drop in flux was due solely to dust and nature of the dust present. To test this scenario, we exact amount of reddening should depend on the quantity become redder as they fade along the extinction vector. The extinction caused by dusty clouds, the obscured stars should become redder as they fade along the extinction vector. The in this case, the magnitude during an obscuration event should be well represented by

\[
V = C + R_{VR} \Delta(V-R),
\]

where \(C\) is the baseline flux, \(\Delta(V-R)\) is the change in the star's color, and \(R_{VR} = A_V/E(V-R)\) is the ratio of total to selective extinction for the bands we observed. The \(V\)-band light curve of each candidate was fitted to determine the value of \(R_{VR}\).

We expect that if the drop in flux was only due to varying amounts of dust (producing varying degrees of extinction), the reduced \(\chi^2\) of this fit should be close to 1. However, if the drop in flux is caused by variability that is not consistent in the two passbands, the fit will be poor. Furthermore, if the dust composition within a cloud follows standard dust properties, the value of the extinction should be similar to that expected for standard reddening law \(R_V = A_V/E(B-V) = 3.1\) (Cardelli, Clayton, & Mathis 1989). However, there is some evidence for variations from the standard extinction law toward the Galactic bulge. For example, Udalski (2003) found \(R_V\) values between 1.8 and 3.3 in the extinction ratio for Galactic bulge fields. Low \(R_V\) values have also been observed by Szomoru & Guhathakurta (1999), who found \(R_V \leq 2\) for a sample of Galactic cirrus clouds. However, Clayton & Cardelli (1988) reported that extinction values are typically between 2.6 and 5.5. The observed differences in \(R_V\) from the standard value have been attributed to variations in silicate and graphite grain size distributions (Kim, Martin, & Hendry 1994; Larson et al. 2000). To be comprehensive in our candidate event selection, we selected light curves having fit coefficients corresponding to \(R_V\) between 1.8 and 5.5. Using the relative extinction for our passbands from by Schlegel, Finkbeiner, & Davis (1998), we transform our results from \(R_{VR}\) to \(R_V\). We adopted the same \(R_{VR}\) limits for the candidate light curves toward all targets. Variations in the value of \(R_V\) may be present toward the LMC and SMC (Zaritsky 1999; Gochermann & Schmidt-Kaler 2002), but these are likely to be within our limits.

The reduced \(\chi^2\) fit value is sensitive to how well the magnitude uncertainties are determined and whether the dust composition varies within a cloud. The flux measurement uncertainties are highly unlikely to be incorrect by more than a factor of 3. The degree of variation in the dust composition within a cloud is completely unknown, but it seems unlikely to be large. Most of the light curves are well sampled with a few hundred data points. Therefore, it seems unlikely that a \(\chi^2\) value greater than 12 could occur even with poorly estimated photometric uncertainties and varying dust composition within a cloud. In Figure 3, we plot the values of \(R_V\) for the MACHO \(V\)-band light curves against the reduced \(\chi^2\) values of the fit.

Of the remaining candidates, 10 bulge, 2 LMC, and 0 SMC light curves passed our extinction criteria. In Table 2, we present the number of candidate obscuration events remaining after each selection criterion was applied. From

\[
\chi^2 > 12 \quad \text{or} \quad R_V < 1.8.
\]

\begin{table}[h]
\centering
\caption{Candidate Obscuration Events}
\begin{tabular}{lcccccc}
\hline
Target & \(C_{Init}\) & \(C_{col}\) & \(C_{CA}\) & \(C_{var}\) & \(C_{HPM}\) & \(C_{RVR,\chi^2}\) \\
(1) & (2) & (3) & (4) & (5) & (6) & (7) \\
\hline
Bulge & 5284 & 372 & 217 & 128 & 83 & 10 \\
LMC & 6427 & 441 & 431 & 151 & 133 & 2 \\
SMC & 678 & 98 & 96 & 37 & 36 & 0 \\
\hline
\end{tabular}
\end{table}

Note.—Candidates present toward the various targets after apply various selections. Col. (2), initial candidates. Col. (3), color cuts are used to remove bright red variables. Col. (4), removing chromospherically active stars. Col. (5), removing Be and semiperiodic variable stars. Col. (6), removing high proper motion stars. Col. (7), removing objects with fits \(\chi^2 > 12\) or \(R_V < 1.8\).
examination of their light curves, it seems likely that most, if not all, of these light curves are due to variability rather than extinction effects. Furthermore, they do not appear to be near the location representative of the most common stars (in the CMD). This suggests that they are simply outliers among the thousands of variable stars present in the fields.

In Figure 4, we present the light and color curves for the Galactic bulge candidate that appears the most like that expected for a cloud transit event. In this case, the object gets redder when it fades as expected for a cloud transit. For the standard reddening law ($R_V = 3.1$), we expect to measure $R_{V,R} = 5.2$ in our filters. The fit of the light curve of this candidate gives $R_{V,R} = 5.1 \pm 0.1$. Although the agreement is very good, the photometry of the faint data points is very uncertain. Almost all of the other candidate’s light curves exhibit drops less than 1 mag. However, the Galactic bulge light curve with MACHO identification number 120.21786.958 has a drop of more than 3.5 mag and is also a good candidate obscuration event. If any of the other candidates were due to dark cloud events, they would have to have a very small dust-to-gas ratio compared to molecular clouds. The lack of a significant number of obscuration event detections is significant but must be quantified to provide a useful limit on cloud models.

4. DETECTION EFFICIENCIES

To determine the significance of our result, it is necessary to know how the selections we have made will affect our efficiency of detection. Any obscuration event will have a start time, a timescale, a maximum extinction, and an impact parameter. The expected occultation timescale distribution for virialized dark clouds with $T = 10$ K and $R = 7$ AU in fields toward the Galactic bulge, LMC, and SMC is given by KBS. The KBS models consider two possible dark cloud populations, a halo one and a disk one. The halo model consists of clouds in an isothermal halo with a core radius of 5 kpc, a local density of $0.01 M_\odot$ pc$^{-3}$, and a Gaussian velocity dispersion of 156 km s$^{-1}$. The disk model consists of a sech$^2$ disk with scale length 2.5 kpc, scale height 190 pc, and a density of $0.03 M_\odot$ pc$^{-3}$. Here the Galactic rotational velocity of the clouds and stars is taken to be 220 km s$^{-1}$ with 25 km s$^{-1}$ dispersion. Although our analysis should be sensitive to a broader range of possible cloud parameters than those of KBS, their models are well constrained. Therefore, we will determine how efficiently dark clouds following the KBS models would have been detected in our analysis. For simplicity, we assumed that the dust was isotropically distributed within each cloud and that the obscuring clouds should not exhibit any preference in their alignment with background stars. We have, therefore, selected cloud-star obscuration impact parameters from a uniform distribution between 0 and 1 cloud radii. To determine our sensitivity to varying amounts of dust, we assumed a uniform distribution of the dust-to-gas fraction relative to Galactic molecular clouds, $f$, to be between 0 and 0.1. This ratio corresponds to a visual extinctions between 0 and 12 mag (Binney & Merrifield 1998). For our analysis, an extinction of 12 mag corresponds to the opaque cloud limit since even the brightest stars in our fields would become undetectable.

For us to have detected any occultation events within our analysis, it would have to either start or finish within the observing period of the MACHO project. Therefore, we produced a randomly distributed set of artificial extinction events lying within the observational time frame. For each of the Galactic bulge, LMC, and SMC data sets, we produced $\sim$10 million artificial events. Many events were added to the same light curves in one data set (corresponding to a $2' \times 2'$ region) for each of the 182 fields we analyzed. Each of these data sets typically contain the photometry for a few thousand stars. Although this is only a small fraction of the stars within a field, we believe this number was sufficient to represent the overall properties of a field since the observational properties will be the same throughout a field. As there were less than 10 million stars chosen toward each target, we added a number of artificial obscuration events to each light curve. These extinction events were added to both red and blue MACHO light curves. The observed drop in flux for each light curve was calculated from the optical depth through the cloud at the cloud-star impact parameter. The extinction was taken to follow the standard reddening law ($R_V = 3.1$). Light curves with the artificial cloud obscuration events were processed through the same selections as the real data up to the point where we removed the chromospherically active stars. At this point, there were a few hundred objects found toward each target in our survey. We have not attempted to parameterize and implement the additional selections here since this would be a very complex and somewhat contrived process. However, we believe the selections we made to remove the variable stars, etc., were fairly robust and would have little effect on our calculated detection efficiency.

In Figure 5, we show the distribution of artificial obscuration events recovered for the Galactic bulge, LMC, and SMC. For all targets, the peak detection efficiency is around 350 days. In general, as the timescale of the obscuration...
events increases, the signal-to-noise ratio of even a small drop in flux increases. However, at longer timescales, the events are more likely to be occurring at the beginning of the light curve where the baseline is determined. Therefore, no dip is measured relative to the median magnitude. At very long timescales, such clouds are more likely to be transiting throughout the observation time. Almost all obscuration events lasting less than 10 days are not detected because of the minimum timescale cut we imposed.

In Figure 6, we plot the cumulative number of events expected for the KBS models. For disk clouds, the largest number of events per star is expected toward the Galactic bulge, while for a halo cloud population, the largest number of events per star is expected toward the SMC. In Figure 7, we plot the number of event detections expected when the stellar exposure time is considered. The total exposure for each target is the sum of the number of stars monitored in a field multiplied by the number of years it was monitored. If dark clouds following the KBS disk model contribute a third of disk mass density ($0.03 M_\odot pc^{-3}$), then $\sim$100,000 extinction events should have been discovered toward the Galactic bulge. Such a large number of events could not have gone undetected in the data. For clouds in the KBS isothermal halo model, the maximum number of events would have been observed toward the Galactic bulge rather than the LMC or SMC. This is somewhat surprising, but is simply due to the fact that twice as many stars were observed toward the Galactic bulge as the LMC. For this model, we should have detected $\sim$50,000 events due to cloud extinctions.

The KBS models have peaks in their transit timescale distributions at around 60 days for halo clouds and 100 days for disk clouds (observed toward the bulge). These models assume masses of $10^{-3}$ and temperatures of 10 K. To extend our limits on KBS models to objects with different tempera-

**Fig. 5.**—Number of recovered events ($R$) as a function of their input obscuration event timescales. **Solid lines:** Obscuration events detection efficiencies toward Galactic bulge fields. **Dotted line:** LMC fields. **Dashed line:** SMC fields.

**Fig. 6.**—Expected cumulative event rate for the KBS models of dark cloud occultations toward the Galactic bulge, LMC, and SMC when detection efficiencies are taken into account. **Solid lines:** Events toward the Bulge fields. **Short-dashed lines:** Events toward the LMC. **Long-dashed lines:** Events toward the SMC. **Bold lines:** KBS model disk events. **Thin lines:** Halo events. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 7.**—Cumulative number of cloud obscuration events expected with our analysis for the KBS models. **Solid lines:** Events toward the Bulge fields. **Short-dashed lines:** Events toward the LMC. **Long-dashed lines:** Events toward the SMC. **Bold lines:** KBS model disk events. **Thin lines:** Halo events. [See the electronic edition of the Journal for a color version of this figure.]
virial radius for a gas cloud is simply given by

\[ R_{\text{vir}} = 7 \text{ AU} \left( \frac{M}{10^{-3} M_\odot} \right) \left( \frac{10 \text{ K}}{T} \right), \]

where \( M \) is the cloud mass and \( T \) the temperature. Using this relationship, we have determined the dark cloud of temperatures and masses that would shift the transit timescale peak from the KBS model to our limits of 15 and 2000 days, respectively. In our experiment, we should have detected dark cloud events between the corresponding masses and temperatures. The results of Lawrence (2001) suggest that clouds should have temperatures less than 18 K but greater than 3 K.

In Figure 8, we have plotted the mass and temperature limits derived from our results. In this figure, we include the cloud mass limits from Rafikov & Draine (2001; \( 2 \times 10^{-2} > M > 10^{-4} M_\odot \)), which are consistent with the results of Kalberla et al. (1999) and all but the most massive cloud model of Lawrence (2001). Mass and temperature regions where this experiment may have missed a population of halo clouds are denoted \( a \) and \( b \) in Figure 8. For a disk cloud population, the regions where we may miss clouds are denoted \( c \) and \( d \). The rate of transits, \( \Gamma \), is proportional to \( T^{-1} \). So varying the cloud temperature from 10 K within these limits only changes the number of events by a small factor. It is clear from this figure that cool massive clouds or warmer low-mass clouds remain possibilities.

4.1. Efficiencies at Low Extinction

The number of events that we expect to detect is strongly dependent on the amount of extinction they cause. For extinctions greater than \( \sim 1 \) mag \(( f \sim 0.08)\), the obscuration event detection efficiency is approximately constant for all targets. To better quantify the number of obscuration events expected if the dark clouds have very small dust concentrations \((<1\% \text{ of molecular clouds})\), we performed a second set of detection efficiency simulations for extinctions less than 1 mag.

In Figure 9, we present the number of low extinction clouds we expect to have detected in our analysis for the KBS models. In this case, we still expect to have detected 20,000 events toward the bulge for disk clouds or 9000 if the clouds exist in an isothermal halo population. In Figure 10, we present the obscuration event detection efficiency as a function of the extinction caused by the cloud. The differences between the plotted detection efficiencies are mainly due to the different timescale distributions. The expected number of detections only falls to zero near the 0.2 mag \(( f \sim 0.02\%)\) because of the cut we imposed in our selection. A nonstandard extinction law would allow a larger amount of dust to go unnoticed. However, this would only change the result by a factor of \( \sim 2 \).

The dark cloud occultation event timescale is proportional to the cloud size \( R \) and the event rate is proportional to \( T^{-1} R^{-1} \). In this analysis, we have assumed the KBS model values \(( T = 10 \text{ K}, M = 10^{-5} M_\odot, \text{ and } R = 7 \text{ AU})\). For different dark cloud models, the extinction events may appear as many short events or a small number of longer timescale events. For the adopted model, halo events peak in number at around 60 days, while for disk clouds, the peak is near 100 days. From our efficiencies, we should still have been able to detect obscuration events due to small clouds (with maximum \( \sim 10 \) days) or due to large clouds (with maximum number \( \sim 1000 \) days) because the cloud transit timescale distributions are broad. However, F. de Paolis (2002, private communication) suggests that there are models in which large halo clouds would take \( 10-100 \) yr to transit a background star. In such cases, we still expect to have
discovered a few clouds as they began to obscure stars (provided they produced more than 0.2 mag of visual extinction). Our results do not show any trace of a low-mass dark cloud population.

5. DISCUSSION

In our analysis, we have attempted to maximize our efficiency for detecting dark cloud obscuration events over a range of characteristic timescales and degree extinctions. Our selection process should have allowed us to detect extinctions due to passing clouds even if they were nonspherical or had an internal dust distribution that was slightly anisotropic. However, we do not find any evidence for a population of dark clouds in either the disk or halo of our Galaxy. We can strongly rule out the existence of a population of opaque clouds with the parameters of the KBS disk or halo model. Furthermore, our results seem to rule out most possible populations of dark clouds with masses from $10^{-4}$ to $2 \times 10^{-2} M_\odot$ and temperatures $T < 18$ K.

There are a number of possible ways a population of gaseous clouds may have been missed in this analysis. For instance, such clouds could have a very small dust content and therefore be almost completely transparent. If the clouds are optically thin ($A_V < 0.2$), our results provide weaker constraints. In this regard, Heithausen (2002) has recently detected two small low extinction molecular clouds that may be part of a dark cloud population with ($A_V < 0.2$). However, in such cases, gas lensing events can still occur. The mass and radius limits for possible clouds from Rafikov & Draine (2001) are approximately $10^{-4} \lesssim M \lesssim 2 \times 10^{-2} M_\odot$, $R < 200$ AU (see their Fig. 9). Combining our results with those of Rafikov & Draine (2001), these results exclude opaque cloud populations with a polytropic index of 1.5. Whether the proposed population of gaseous clouds are dusty is not certain. However, as we mentioned earlier, if the SCUBA sources of Lawrence (2001) are due to dark clouds, the presence continuous emission in the submillimeter band could be due to the presence of dust. The existence of dusty molecular clumps is also useful for explaining the EGRET background γ-ray emission results (Kalbera et al. 1999). It is possible that the dust in the clouds would not be readily observed from stellar obscuration events. For instance, the dust may sediment to the core of the cloud (Wardle & Walker 1999). Alternatively, the clouds may be clumped into large dark clusters that exist only in regions far from the Galactic disk (Wasserman & Salpeter 1994; de Paolis et al. 1995, 1998).

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