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DARK MATTER AND BROWN DWARFS: PROSPECTS FOR THE DIRECT DETECTION OF A BROWN DWARF HALO

RUTH A. DALY AND GAIL C. MCLAUGHLIN
Department of Physics, Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544
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ABSTRACT

Very low mass objects, referred to as brown dwarfs, could comprise the halo dark matter of galaxies. The possibility of directly detecting infrared emission from brown dwarfs is discussed here. The direct detection of the emission from brown dwarfs that could comprise the halo dark matter of a nearby galaxy, dark matter in a nearby cluster of galaxies and in distant galaxies and clusters of galaxies, and from individual brown dwarfs within our own Galaxy are discussed.

The integrated infrared emission of the halo of a nearby galaxy could be detected or constrained by pointed observations if the halo is comprised of brown dwarfs with a mass in the range from $\sim 10^{-1}$ to 10^{-3} $M_\odot$ and an age of $\sim 10^{10}$ yr. The position and density profile of the halo are known. The expected infrared surface brightness is low, but could be detected with *ISO* or *SIRTF*. Extended sources, such as a nearby galaxy or cluster of galaxies, can best be observed at short wavelengths, since at longer wavelengths it is difficult to correct for galactic cirrus and zodiacal emission, so higher mass brown dwarfs ($M \gtrsim 5 \times 10^{-3}$ $M_\odot$) will be most seriously constrained as a dark matter candidate. Similarly, the integrated infrared emission from clusters of galaxies will provide an interesting constrast on, or detection of, brown dwarfs as a cluster dark matter candidate.

Individual brown dwarfs in the solar vicinity with an age of $\sim 10^{10}$ yr, and mass in the range from $\sim 10^{-1}$ to 10^{-3} $M_\odot$, could be detected or constrained as a halo dark matter candidate with a survey which covers a substantial fraction of the sky to 10–0.1 mJy levels, or which covers an area that is a few square degrees to 100–1 μJy levels, over the wavelength range from ~ 4 to 150 μm. Since individual brown dwarfs in the solar vicinity are point sources, they can be observed or constrained at both long and short wavelengths. Observations with *SIRTF* or *ISO* could either detect individual brown dwarfs in the solar vicinity or significantly constrain them as a halo dark matter candidate.

Subject headings: dark matter — Galaxy: halo — stars: low-mass, brown dwarfs

1. INTRODUCTION

It has long been known that the rotational velocity of gas in spiral galaxies as a function of distance from the center of the galaxy is roughly constant, indicating that the galaxies have a significant amount of unseen matter. This matter may be baryonic or nonbaryonic (e.g., Faber & Gallagher 1979; Trimble 1987). If the dark matter is baryonic, it could be in the form of very low mass objects such as brown dwarfs.

It is very important to attempt to observe the brown dwarfs directly and hence either observe them or significantly constrain them as a dark matter candidate. If it were found that brown dwarfs do not comprise the halo dark matter, the argument for nonbaryonic dark matter would be significantly strengthened. The necessary observations could be carried out with the *Infrared Space Observatory* (*ISO*) or the *Space Infrared Telescope Facility* (*SIRTF*).

If brown dwarfs comprise the halo dark matter of galaxies, they are likely to be fairly old since the galaxies themselves are fairly old. For brown dwarfs with a fixed age, such as 10^{10} yr, the brown dwarf mass determines the wavelength at which the brown dwarf emits most of its light. Observations at a single wavelength only constrain halo brown dwarfs with a small range of masses. For example, observations at a wavelength of 3 μm constrain the fraction of the halo dark matter made up by brown dwarfs with a mass of $\sim 10^{-1}$ $M_\odot$ if the dwarfs have an age of $\sim 10^{10}$ yr. In order to detect or constrain brown dwarfs with a range of masses, observations must be carried out over a range of wavelengths. Observations over the wavelength range from a few microns to ~ 150 μm would constrain brown dwarfs with masses in the range from $\sim 10^{-1}$ to 10^{-3} $M_\odot$ given that the brown dwarfs have an age of $\sim 10^{10}$ yr.

Searching for the integrated infrared emission from halo brown dwarfs in a nearby galaxy has the attractive feature that the position and expected density profile of the halo are known. A nearby edge-on-spiral galaxy would be ideal; the infrared spectrum could be used to locate the dust, and the dust emission could be subtracted off. However, due to the large extent of these halos and the presence of foreground radiation fields produced by cirrus within our Galaxy and zodiacal emission, it appears that these observations can only be realized at wavelengths less than ~ 50 μm (C. A. Beichman 1991, private communication). In a spiral galaxy, the dust should dominate along the major axis, and the brown dwarf emission could be constrained or detected along the minor axis, as discussed, for example, by Skrutskie, Shure, & Beckwith (1985) and van der Kruit (1987).

In late-type galaxies, it is unlikely that stars will contribute to the flux, especially as one goes to wavelengths greater than a few microns (Skrutskie et al. 1985; Jensen & Thuan 1982; Boughn, Saulson, & Seldner 1981; Beichman et al. 1990). It is very important that the observations be done at several wavelengths so that brown dwarfs with a range of masses can be constrained, and so that dust, stars, or brown dwarfs that are observed can be identified by their colors.

Radiation produced by stars or dust within the nearby galaxy can be distinguished from emission from the brown dwarf halo by the density profile of the radiation field, since the density profile of the brown dwarf halo can be estimated from the rotation curve of the galaxy. Local and Galactic foreground radiation fields must be subtracted to allow interesting limits on or a detection of the halo to result. Galactic cirrus is well correlated with galactic H I gas (Boulanger & Perault 1988), which could be used to subtract off this foreground radiation. Repetition of the observations at different times would allow different zodiacal foregrounds to be subtracted, adding to the significance of the limit or detection.

Another method to directly detect or significantly constrain brown dwarfs as a halo dark matter candidate is to search for individual brown dwarfs in the solar vicinity; again, for the reasons stated above, it is very important that the search be carried out at several different wavelengths. Searching for individual brown dwarfs in the solar vicinity has the positive feature that individual brown dwarfs are point sources, so confusion due to galactic cirrus and zodiacal emission are not so problematic. However, it has the negative feature that the search is blind: it is not known a priori where the brown dwarfs are located. A search for individual brown dwarfs is best done with a survey that covers a substantial fraction of the sky, although a deep survey which covers a small solid angle may suffice (§ 2.2).

Distant galaxies and clusters of galaxies in which brown dwarfs formed recently are expected to be very bright infrared sources, as discussed in § 2.3. Observations of these systems could detect the brown dwarfs or place significant constraints on their contribution to the dark matter in these systems.

At the present time, the constraints on brown dwarfs as a dark matter candidate are weak (e.g., Low 1986; van der Kruit 1987; Skrutskie et al. 1985; Beichman et al. 1990). However, new advances in detector technology may now make it possible to detect brown dwarfs directly, or place severe limits on the allowed mass range of brown dwarfs that could comprise the halo dark matter.

Jura (1988) and Adams & Walker (1990) discuss the detection of the brown dwarf halo of a nearby edge-on spiral galaxy. Adams & Walker suggest that the brown dwarf halo of the Galaxy can be directly detected. Low (1986) and Beichman et al. (1990) discuss the possibility of detecting an individual brown dwarf in the solar vicinity. Here, the possibilities of detecting the brown dwarf halo of a nearby galaxy (§ 2.1.1), a nearby cluster of galaxies (§ 2.1.2), individual brown dwarfs in the vicinity of the Sun assuming that these contribute to the halo dark matter of the Galaxy (§ 2.2), the brown dwarf halos of distant galaxies and clusters of galaxies that are relatively old (§ 2.3.1), and those that are quite young (§ 2.3.2) are considered in detail. The observing times required to detect an individual brown dwarf in the solar vicinity and to detect the halo of a nearby galaxy using *SIRTF* are discussed in § 3. The results are summarized in § 4.

2. OBSERVABLE QUANTITIES

2.1. *The Brown Dwarf Halo of a Nearby Galaxy*

The ideal spiral galaxy for the observation of the integrated emission from the brown dwarfs that (hypothetically) comprise the dark halo is one which is edge-on, has a minimum of dust emission, and has a small bulge component. Massive elliptical galaxies that are nearby may also have detectable brown dwarf halos.

The spectrum of an individual brown dwarf is assumed to be a blackbody at wavelengths greater than a few microns. The spectrum of the dwarf peaks at a frequency given by the effective temperature of the dwarf. The integrated emission or luminosity of the brown dwarf halo at this frequency is a maximum when all of the dwarfs that comprise the halo have the same mass (assuming that the objects are indeed brown dwarfs, that is, they are not massive enough to have nuclear reactions); brown dwarfs in the mass range from $\sim 10^{-1}$ to 10^{-3} $M_{\odot}$ are considered here. Initially, the mass function for the brown dwarfs is assumed to be a delta function: all of the brown dwarfs have the same mass. Given that the brown dwarfs all have a similar age (e.g., 10^{10} yr), observations at a fixed frequency will constrain or detect brown dwarfs with a fixed mass. If the flux limit is some fraction $f_{\rm hm}$ of the flux predicted assuming a delta function (at a mass given by the wavelength of the observation) then dwarfs with this mass must comprise less than $f_{\rm hm}$ of the halo dark matter as discussed in § 2.1.1; $f_{\rm hm}$ stands for the "fraction of the halo mass."

Note that there is no good way to estimate the mass function of the brown dwarfs. If brown dwarfs comprise the halo dark matter, they surely formed under conditions very different from those in the disk of the Galaxy, or even in globular clusters. Perhaps a good first approximation is a Gaussian distribution of masses, in which case the brown dwarf mass at which the Gaussian peaks corresponds to the brown dwarf mass discussed here. The factor by which the predicted flux decreases for a Gaussian distribution of masses depends on the width of the Gaussian.

Given that the total mass of the dark halo is M and that individual brown dwarfs all have the same mass m, the number of dwarfs per galaxy is $N = M/m$. The total luminosity of the galaxy ($L \equiv dE\ dt^{-1}$), the luminosity density ($L_\nu \equiv dE\,dt^{-1}\,d\nu^{-1}$), the flux density ($f_\nu \equiv dE\,dt^{-1}\,dA^{-1}\,d\nu^{-1}$), and the surfaces brightness ($S_\nu \equiv dE\,dt^{-1}\,dA^{-1}\,d\nu^{-1}\,d\Omega^{-1}$) can be estimated using the evolution model of Stevenson (1986), given a mass, age, and opacity for the brown dwarfs. Note that the numerical codes and Stevenson's analytic expressions are in good agreement (Nelson, Rappaport, & Joss 1986; Nelson 1990). The brown dwarfs are likely to be composed of very low metallicity material; in this case the opacity and hence the luminosity of the dwarfs decreases, although the effect on the luminosity at late times is small (Nelson 1990) and is therefore neglected here.

The mass of the galaxy within a radius of 50 kpc is assumed to be 10^{12} $M_{\odot}$, equivalent to assuming a rotational velocity of 300 km s^{-1} for a spiral galaxy; the fluxes and flux densities scale in proportion with the mass of the galaxy.

The luminosity L of a halo of mass $M \simeq 10^{12}$ $M_{\odot}$ is $L = NL_{\rm bd}$, where $L_{\rm bd}$ is the luminosity of an individual brown dwarf (Stevenson 1986), and $N \simeq 10^{14} m_{-2}^{-1}$. The total luminosity is

$$\frac{L}{L_{\odot}} \simeq 3.5 \times 10^{6} m_{-2}^{1.5} t_{10}^{-1.25} \kappa_{-2}^{0.3} , \qquad (1)$$

where m_{-2} is the mass of a dwarf in units of 10^{-2} $M_{\odot}$, t_{10} is the age of the brown dwarfs in units of 10^{10} yr, and κ_{-2} is the opacity of a dwarf in units of 10^{-2}. Note that for $m \simeq 10^{-1}$ $M_{\odot}$ this expression is valid for ages $t \gtrsim 8 \times 10^{8}$ yr; for

$m \simeq 10^{-2}\ M_\odot$ this expression is valid for ages $t \gtrsim 2 \times 10^8$ yr; for $m \simeq 10^{-3}\ M_\odot$ this expression is valid for $t \gtrsim 3 \times 10^7$ yr (Stevenson 1986). Since the spectrum is assumed to be that of a blackbody, the luminosity density $L_{\nu_{\max}}$ at the frequency of maximum emission $\nu_{\max}$ may be obtained from the total luminosity if the effective temperature of an individual dwarf is known:

$$\frac{L_{\nu_{\max}}}{L} \simeq \frac{0.62}{\nu_{\max}}\ , \tag{2}$$

where $\nu_{\max}$ is the frequency at which the Planck function $B_\nu(T)$ peaks:

$$\nu_{\max} \simeq 2.8\,\frac{kT}{h} \simeq 1.3 \times 10^{13} m_{-2}^{0.79} t_{10}^{-5/16} \kappa_{-2}^{0.075}\ \mathrm{Hz} \tag{3a}$$

$$\lambda(\nu_{\max}) \equiv \frac{c}{\nu_{\max}} \simeq 23\ \mu\mathrm{m}\ m_{-2}^{-0.79} t_{10}^{0.31} \kappa_{-2}^{-0.075}\ , \tag{3b}$$

where the effective temperature T of the dwarf as a function of mass, age, and opacity given by Stevenson (1986) has been used. The luminosity density is

$$L_{\nu_{\max}} \simeq 6.3 \times 10^{26} m_{-2}^{0.71} t_{10}^{-0.94} \kappa_{-2}^{0.23}\ \mathrm{ergs\ s^{-1}\ Hz^{-1}}\ . \tag{4}$$

The flux density of a brown dwarf halo of mass $M \simeq 10^{12}\ M_\odot$ which is a distance x Mpc away (neglecting the expansion of the universe) at the frequency at which the emission peaks $\nu_{\max}$ (see eqs. [3]) is

$$f_{\nu_{\max}} \simeq 0.52 x^{-2} m_{-2}^{0.71} t_{10}^{-0.94} \kappa_{-2}^{0.23}\ \mathrm{Jy}\ , \tag{5}$$

where 1 Jy is 10^{-23} ergs cm^{-2} s^{-1} Hz^{-1}.

In terms of the wavelength of peak emission, the mass per brown dwarf is (see eq. [3b])

$$m_{-2} \simeq \left(\frac{\lambda_{\max}}{23\ \mu\mathrm{m}}\right)^{-1.27} t_{10}^{0.4} \kappa_{-2}^{-0.095}\ . \tag{6}$$

Given the mass per brown dwarf, the wavelength at which the flux density peaks is fixed, and vice versa. In terms of $\lambda_{\max} \equiv \lambda(\nu_{\max})$ the flux density (eq. [5]) is

$$f_{\nu_{\max}} \simeq 0.52 x^{-2} \left(\frac{23\ \mu\mathrm{m}}{\lambda_{\max}}\right)^{0.9} t_{10}^{-0.66} \kappa_{-2}^{0.16}\ \mathrm{Jy}\ . \tag{7}$$

The density of the dark matter is assumed to be spherically symmetric and $\propto r^{-2}$, r being the radial coordinate of a point in the galaxy; the dark matter distribution is assumed to have a negligible core radius. The projected separation $s_\perp$ of a point in the halo from the center of mass of the halo is some fraction β of the total (virial) radius R_T of the galaxy, $\beta \equiv s_\perp/R_T$; R_{50} is the total radius of the galaxy in units of 50 kpc. The surface brightness of the halo at the frequency at which the emission peaks $\nu_{\max}$ is

$$S_{\nu_{\max}} \simeq 35 m_{-2}^{0.71} t_{10}^{-0.94} \kappa_{-2}^{0.23} R_{50}^{-2} \beta^{-1} \times \arctan\left(\sqrt{\beta^{-2} - 1}\right)\ \mathrm{Jy\ sr^{-1}}\ . \tag{8}$$

Hence,

$$S_{\nu_{\max}} = k_1 s_\perp^{-1} \tan^{-1} \sqrt{\beta^{-2} - 1}\ ,$$

which defines the constant k_1.

TABLE 1

SURFACE BRIGHTNESS OF THE HALO OF A NEARLY GALAXY[a]

m ($M_\odot$) (1)	$\lambda(\nu_{\max})$ (μm) (2)	β ($s_\perp/R_T$) (3)	S_ν (Jy sr^{-1}) (4)
10^{-1}	3.7	0.05	5.5×10^3
		0.1	2.5×10^3
		0.3	760
10^{-2}	23	0.05	10^3
		0.1	500
		0.3	140
5×10^{-3}	40	0.05	640
		0.1	310
		0.3	90
10^{-3}	142	0.05	200
		0.1	100
		0.3	30

[a] See § 2.1.

Note that young brown dwarfs have a significantly larger luminosity and surface brightness, and emit most of their energy at higher frequencies, than older brown dwarfs. Higher mass dwarfs have a significantly higher luminosity and surface brightness, and emit most of their energy at higher frequencies, than lower mass dwarfs. The surface brightness of the halo is much larger at small β (i.e., close to the center of the galaxy) than it is at larger projected separations from the center of mass of the halo.

Using the expressions given above, the surface brightness and luminosity of a $10^{12}\ M_\odot$ halo have been estimated for brown dwarfs with an age of $\sim 10^{10}$ yr and masses m in the range from 10^{-1} to $10^{-3}\ M_\odot$ at various projected separation from the center of mass of the system $s_\perp$ relative to the total radius of the galaxy R_T: $\beta \equiv s_\perp/R_T$ (see Table 1). Column (1) of Table 1 indicates the mass of an individual brown dwarf (in solar masses); column (2) lists the wavelength of peak emission for a brown dwarf with the mass listed in column (1) and an age of $\sim 10^{10}$ yr; column (3) indicates the projected separation of a region in the galaxy in units of the total radius of the galaxy (where R_{50} in eq. [8] has been set equal to 1); and column (4) indicates the surface brightness at the position β indicated in column (3) for a brown dwarf age of 10^{10} yr.

Table 2 illustrates how the total luminosity, wavelength of peak emission, and effective temperature vary with the age of

TABLE 2

INTEGRATED HALO EMISSION FROM A $10^{12}\ M_\odot$ GALAXY[a]

m ($M_\odot$) (1)	Age (yr) (2)	L ($L_\odot$) (3)	$\lambda(\nu_{\max})$ (μm) (4)	T (K) (5)
10^{-1}	10^{10}	1.1×10^8	3.7	1.4×10^3
	10^9	2×10^9	1.8	2.9×10^3
	10^8	3.5×10^{10}	0.9	5.9×10^3
10^{-2}	10^{10}	3.5×10^6	23	220
	10^9	6.2×10^7	11	470
	10^8	1.1×10^9	5.5	940
5×10^{-3}	10^{10}	1.2×10^6	40	130
	10^9	2.1×10^7	19.5	260
	10^8	3.8×10^8	9.5	540
10^{-3}	10^{10}	1.1×10^5	142	36
	10^9	2.0×10^6	70	70
	10^8	3.5×10^7	35	150

[a] See § 2.1.

the brown dwarfs. The mass of the brown dwarfs is listed in column (1); the age is indicated in column (2); the total luminosity is given in column (3); the wavelength of peak emission (see eq. [3b]) is indicated in column (4); and the effective temperature is listed in column (5).

2.1.1. *Prospects of Detecting a Brown Dwarf Halo*

The flux that originates from within a circle with projected separation from the center of the galaxy $s_\perp$ may be obtained by integrating the surface brightness over the solid angle $d\Omega$ where $d\Omega = dA/D^2 = 2\pi s_\perp \, ds_\perp/D^2$ where D is the distance from the Earth to the galaxy. Carrying out this integration, the flux from brown dwarfs with projected separations less than $s_{\perp *}$ is

$$f_\nu(s_\perp < s_{\perp *}) = 2\pi k_1 D^{-2} R_T \left\{ 1 + \frac{s_{\perp *}}{R_T} [\arctan(x_*) - x_*] \right\} , \tag{9}$$

where

$$x_* \equiv \sqrt{(R_T/s_{\perp *})^2 - 1} .$$

The fraction of the total flux that originates from within a projected separation $s_{\perp *}$ from the center of the galaxy is

$$\delta \equiv \frac{f_\nu(s_\perp < s_{\perp *})}{f_\nu(s_\perp < R_T)} \simeq 1 - \frac{s_{\perp *}}{R_T} [x_* - \arctan(x_*)] . \tag{10}$$

To determine whether a brown dwarf halo can be detected or significantly constrained let us consider a satellite which can reach a flux of α per pixel, where each pixel has an angular area of $\theta^2_{\rm arcmin}$ arcmin^2. The number of pixels in an annulus is N. The emission from the annulus can be detected when $\gamma > \alpha N^{1/2}$, where the flux in the annulus is γ. The number of pixels in an annulus that extends from $\beta_1 = s_{\perp 1}/R_T$ to $\beta_2 = s_{\perp 2}/R_T$ is $N \simeq \pi R_T^2(\beta_2^2 - \beta_1^2) D^{-2} \theta_{\rm rad}^{-2}$; $\theta^2_{\rm rad}$ is the angular area of a pixel in steradians. For a fixed β_1, both $\gamma = (\delta_2 - \delta_1) f_{\nu_{\rm max}}$ and $N^{1/2}$ are proportional to β_2; hence, both the noise level $\alpha N^{1/2}$ and the flux γ increase at about the same rate as the area enclosed by the annulus increases. So, either each annuli of the halo can be detected, and hence the density profile confirmed, or it is not possible to detect any part of the halo.

Using equations (7) and (10) to obtain γ, assuming $\beta_1 = 0$, and noting that

$$\beta_2^{-1} - \left(\sqrt{\beta_2^{-2} - 1} - \arctan \sqrt{\beta_2^{-2} - 1}\right) \simeq 1 ,$$

the criterion that the brown dwarf halo be detected or constrained is that the flux limit per pixel α satisfy

$$\alpha \lesssim (1.7 \text{ mJy}) \theta_{\rm arcmin} x^{-1} R_{50}^{-1} \left(\frac{\lambda_{\rm max}}{23 \ \mu{\rm m}} \right)^{-0.9} t_{10}^{-0.66} \kappa_{-2}^{0.16} ; \tag{11}$$

recall that x is the distance to the galaxy in Mpc, $x = D/$Mpc. Note that this flux limit per pixel is inversely proportional to the distance to the galaxy, as opposed to the distance squared. This result holds when the flux at a given distance $s_\perp$ from the center of the galaxy is obtained using observations in an annulus about the center of the galaxy, as described above.

Note that it is most desirable to obtain a flux limit that is a factor of 10 to 100 below that indicated by equation (11). If the limit given by equation (11) is reached at a fixed wavelength λ_* and there is no detection, then the halo cannot be completely comprised of brown dwarfs with the single mass given by equation (6) evaluated at $\lambda_{\rm max} = \lambda_*$; let us denote this mass by m_*. However, it is much better to be able to state that brown dwarfs with a mass given by equation (6) must comprise less than 10% (by achieving a flux limit that is 10% of that indicated by eq. [11]), or less than 1% (by achieving a flux limit that is 1% of that indicated by eq. [11]) of the halo dark matter. The upper bound on the fraction $f_{\rm hm}$ of the halo dark matter made up of brown dwarfs with mass m_* is the ratio of the flux limit per pixel reached at λ_* to the flux expected (given by eq. [11]), since the expected flux has been computed assuming that brown dwarfs of mass m_* constitute 100% of the halo dark matter.

The observing times required to detect or constrain the contribution of brown dwarfs to the halo dark matter with an instrument such as *SIRTF* are discussed in § 3.2.

2.1.2. *Prospects of Detecting Brown Dwarfs in a Cluster of Galaxies*

The dark matter in clusters of galaxies could be comprised of brown dwarfs. The mass of dark matter in clusters of galaxies within a radius of ~ 1 Mpc is $\sim 10^{15} \, M_\odot$.

The computation of the flux density and surface brightness of the integrated emission from the dwarfs that may comprise the dark matter in clusters parallels that for galaxy halos given in § 2.1 and § 2.1.1 with the fluxes (e.g., eq. [7]) increased by a factor of 10^3 and the radius increased from 50 kpc to 1 Mpc, or $R_{50} \rightarrow 20 R_{1000}$. Hence, equation (8) for brown dwarf emission associated with the dark matter in a cluster of galaxies is

$$S_{\nu_{\rm max}}({\rm cl}) \simeq 90 m_{-2}^{0.71} t_{10}^{-0.94} \kappa_{-2}^{0.23} R_{1000}^{-2} \beta^{-1} \times \arctan\left(\sqrt{\beta^{-2} - 1}\right) \text{ Jy sr}^{-1} . \tag{12}$$

As in the case for galaxy halos, the prospects for the detection or constraint of brown dwarfs as a dark matter candidate in clusters of galaxies is strongest when the emission from each annulus is combined. In this case the requisite flux limit per pixel (eq. [11]) is increased by a factor of 10^3 due to the increase in the total mass of dark matter and is decreased by a factor of 20 due to the increase in R_{50} to $20 R_{1000}$. However, as discussed in § 3.2, it is desirable to have the entire galaxy or cluster dark matter halo fall on the detector. This means that in practice the distance to the cluster will have to be larger than that to a galaxy, so both x and R_{50} must increase by about a factor of 20, and the requisite flux limit per pixel to be able to detect brown dwarfs associated with cluster dark matter increases by a factor of 2.5 from that given by equation (11) for dark matter associated with the halo of an individual galaxy.

2.2. *Detecting an Individual Brown Dwarf in the Solar Vicinity*

The detection of an individual brown dwarf in the solar vicinity depends on the local number density of brown dwarfs and their flux density. In order to detect a local brown dwarf, or to significantly constrain the number of dwarfs with a given mass which could comprise the halo dark matter, a large fraction of the sky must be surveyed, unless one area is surveyed to a great depth. The frequency of the survey determines the brown dwarf mass that will be most seriously constrained by

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the survey (see eqs. [3] and [6]), and the expected number of detections within the volume surveyed determines the strength of the constraint.

The mean local number density n of brown dwarfs associated with the halo dark matter is $\sim M(4\pi R_s^2 R_T m)^{-1} \simeq 2.5 m_{-2}^{-1}$ pc^{-3}; M is the total mass of the Galaxy, taken to be $10^{12}\ M_\odot$, R_s is the position of the Sun relative to the Galactic center, taken to be 8 kpc, R_T is the total radius of the Galaxy, taken to be 50 kpc, and m is the mass per brown dwarf. Using equations (3), the local number density of brown dwarfs is

$$n[\lambda(\nu_{\max})] \simeq 2.5\left[\frac{\lambda(\nu_{\max})}{23\ \mu\mathrm{m}}\right]^{1.27} t_{10}^{-0.4}\kappa_{-2}^{0.095}\ \mathrm{pc}^{-3}\ . \qquad (13)$$

Each brown dwarf has a luminosity (Stevenson 1986) of $L \simeq 3.5 \times 10^{-8} m_{-2}^{2.5} t_{10}^{-1.25}\kappa_{-2}^{0.3} L_\odot$, and therefore has a luminosity density (see eq. [2])

$$L_{\nu_{\max}} \simeq 6.3 \times 10^{12} m_{-2}^{1.71} t_{10}^{-0.94}\kappa_{-2}^{0.23}\ \mathrm{ergs\ s^{-1}\ Hz^{-1}}\ . \qquad (14)$$

The flux density is $f_{\nu_{\max}} = L_{\nu_{\max}}/(4\pi R^2)$ where R is the distance from the Earth to the brown dwarf; R_{pc} is the distance to the brown dwarf in parsecs. The flux density from an individual dwarf at the frequency $\nu_{\max}$ (see eqs. [3]) is

$$f_{\nu_{\max}} \simeq 5.3 R_{\mathrm{pc}}^{-2} m_{-2}^{1.71} t_{10}^{-0.94}\kappa_{-2}^{0.23}\ \mathrm{mJy}\ . \qquad (15)$$

Using equation (6), the predicted flux density as a function of wavelength $\lambda(\nu_{\max})$ is

$$f_{\nu_{\max}} \simeq 5.3 R_{\mathrm{pc}}^{-2}\left[\frac{23\ \mu\mathrm{m}}{\lambda(\nu_{\max})}\right]^{2.16} t_{10}^{-0.26}\kappa_{-2}^{0.063}\ \mathrm{mJy}\ . \qquad (16)$$

Suppose a program aims to detect N brown dwarfs in the solar vicinity over $4\pi\chi$ steradians. The requisite flux limit of the survey as a function of frequency (or wavelength) is indicated by equation (16) with R such that N objects are expected to be within the volume $V = (4\pi\chi/3)R^3$ surveyed. The total number of dwarfs within this volume is $\simeq n(4\pi\chi/3)R^3$ with n given by equation (13). Setting this equal to N, solving for R and substituting into equation (16) the requisite flux limit as a function of frequency (or wavelength) is

$$f_{\nu_{\max}} \simeq 25\left(\frac{\chi}{N}\right)^{2/3}\left(\frac{\lambda_{\max}}{23\ \mu\mathrm{m}}\right)^{-1.3} t_{10}^{-0.52}\kappa_{-2}^{0.13}\ \mathrm{mJy}\ . \qquad (17)$$

One way to look for individual brown dwarfs in the solar vicinity is to scan a significant fraction of the sky at wavelengths from $\sim$4 to 150 μm (relevant for brown dwarfs that are $\sim 10^{10}$ yr old and are in the mass range from $\sim 10^{-1}$ to 10^{-3} $M_\odot$) to flux levels of $\sim$45 mJy at 4 μm to $\sim$400 μJy at 150 μm (obtained from eq. [17] with $N = 10$ and $\chi = 1$). Such a constraint over wavelengths from $\sim$4 to 150 μm would imply that brown dwarfs in the mass range from 10^{-1} to 10^{-3} $M_\odot$ comprise less than $\sim$10% of the halo dark matter; of course, the brown dwarfs may be detected.

If a small region of the sky is surveyed, then the survey must go to very faint flux levels to detect or constrain brown dwarfs as a halo dark mater candidate. Consider a survey that covers a 2° × 2° region, then $\chi \simeq 10^{-4}$. Suppose that the goal is to determine whether brown dwarfs of mass m_* can make up more than $\sim$10% of the halo dark matter, which indicates a value of N of 10; since a delta function for the mass has been assumed, if we expect to detect 10 dwarfs of mass m_* and see none, then these brown dwarfs must comprise less than 1/10 of the halo dark matter. The flux limit that must be reached at a wavelength λ_* (obtained from eq. [3b] evaluated at $m = m_*$) is $\sim 12\ \mu\mathrm{Jy}(\lambda_*/23\ \mu\mathrm{m})^{-1.3}$ (see eq. [17]).

Note that individual brown dwarfs in the solar vicinity are point sources, and therefore could be detected to very long wavelengths, $\sim$150 μm, although they will be very faint, $\sim\mu$Jy.

The observing times required to detect individual brown dwarfs with an instrument such as *SIRTF* are discussed in § 3; observing strategies are also discussed.

2.3. *Dark Matter in Distant Systems*

2.3.1. *Old Galaxy Halos and Dark Matter in Clusters of Galaxies*

The luminosity of the (hypothetical) brown dwarf halo increases substantially as the age of the brown dwarfs decreases (see Table 2). It is assumed here that the age of the brown dwarfs is comparable to the age of the universe at the redshift of the distant galaxy; that is, it is assumed that the halo formed at a redshift much greater than the redshift of the galaxy. In this case the age of the brown dwarfs comprising the halo is $\sim t_{10} \simeq 1.25(1 + z)^{-1.5}$ for a flat matter-dominated universe; the flux density is maximum in such a cosmological model. A value of Hubble's constant of $100h$ km s^{-1} Mpc with $h = 0.5$, appropriate for such a model, has been assumed.

The flux density at the frequency $\nu_0 = \nu/(1 + z)$ is

$$f_{\nu_0} = \frac{L_\nu}{4\pi a_0^2 r^2(1 + z)}$$

$$\simeq \frac{L_\nu h^2}{4.3 \times 10^{57}(1 + z)(1 - 1/\sqrt{1 + z})^2}\ \mathrm{cm}^{-2}\ . \qquad (18)$$

With the luminosity density given by equation (4), the flux density is

$$f_{\nu_0} \simeq 1.5 \times 10^{-8}\,\frac{m_{-2}^{0.71} t_{10}^{-0.94}\kappa_{-2}^{0.23}}{(1 + z)(1 - 1/\sqrt{1 + z})^2}\ \mathrm{Jy}\ . \qquad (19)$$

At a redshift of 2 the age of the universe and hence of the halo is $\sim t_{10} \simeq 0.24$, and for a brown dwarf mass of $\sim m_{-2} \simeq 1$ the flux density peaks at $\sim 14.7(1 + z)\ \mu$m $\simeq 44\ \mu$m; the flux density is $\sim 0.1\ \mu$Jy. The flux density is even smaller for lower brown dwarf masses. At a redshift of 1, the brown dwarf age is $\sim t_{10} \simeq 0.44$, and, for $m_{-2} \simeq 1$, the flux density peaks at $\sim 18(1 + z)\ \mu$m $\simeq 36\ \mu$m, and the flux density is $\sim 0.2\ \mu$Jy.

Distant galaxies are significantly smaller in angular extent than those nearby; therefore it would be extremely difficult to distinguish brown dwarf emission from dust emission in distant galaxies. It is therefore unlikely that brown dwarfs as a halo dark matter candidate will be detected or constrained by infrared observations of distant galaxies.

The only hope to detect brown dwarf halos of distant galaxies is if the halos form over a very long period of time, so that a galaxy at a redshift of 1 or 2 has a young component to its (hypothetical) brown dwarf halo, as discussed in § 2.3.2. However, it is quite possible that brown dwarfs form only under particular types of conditions; it is possible that they formed in the early history of the universe, or in protogalaxies, and are no longer forming. For example, perhaps brown dwarfs form only in very low metallicity clouds, low-density clouds, clouds which cool via Compton cooling, or clouds with very low magnetic fields.

The flux density due to old brown dwarfs in a clusters of galaxies is about a factor of 10^3 greater than that due to brown dwarfs in a galaxy because the mass of dark matter in a cluster is $\sim 10^{15}\ M_\odot$ while that in a galaxy is $\sim 10^{12}\ M_\odot$. The emission from old brown dwarfs comprising the cluster dark matter at a redshift of 2 would be $\sim 100 f_{\rm hm}$ μJy at ~ 44 μm if brown dwarfs with a mass of m_{-2} comprise a fraction $f_{\rm hm}$ of the mass of the dark matter, and that from a cluster at a redshift of 1 would be $\sim 200 f_{\rm hm}$ μJy and would be detected at ~ 36 μm.

2.3.2. *Young-Galaxy Halos and Dark Matter in Clusters of Galaxies*

Brown dwarfs may form as a galaxy or cluster of galaxies forms, as discussed, for example, by Fabian, Arnaud, & Thomas (1986). If the dark matter in the galaxy or cluster of galaxies forms at relatively low redshifts, such as 1 or 2, the brown dwarfs will be relatively young, the infrared emission from the brown dwarfs will be substantial, and the emission wavelength will be shorter than for older brown dwarfs with a similar mass. Brown dwarfs can be detected or constrained as a halo or cluster dark matter candidate if they formed recently.

The flux density from a galaxy can be obtained from equation (19), and that from a cluster is about a factor of 10^3 greater than that from a galaxy because the mass of dark matter in a cluster is $\sim 10^{15}\ M_\odot$ while that in a galaxy is $\sim 10^{12}\ M_\odot$. For example, the flux density from a galaxy or cluster of galaxies, at a redshift z, that would be detected at a wavelength of $\lambda \simeq 5.5$ μm $m_{-2}^{-0.79} t_8^{0.31} \kappa_{-2}^{-0.075}(1+z)$ (see eq. [3b]) from brown dwarfs with an age of $10^8 t_8$ yr can be computed from equation (19). For $t_8 \simeq 1$ and $z \simeq 2$, the flux density from a galaxy is ~ 2 μJy $m_{-2}^{0.71}\kappa_{-2}^{0.23}$ and that from a cluster is about a factor of 10^3 larger and is 2 mJy $m_{-2}^{0.71}\kappa_{-2}^{0.23}$. If the brown dwarfs have an age of $\sim 10^9$ yr and are at a redshift of ~ 2 these flux densities decrease by about a factor of 9.

Therefore, the flux densities from young brown dwarfs in galaxies and clusters of galaxies at redshifts of ~ 2 could be detected, or the fraction of the dark matter comprised of brown dwarfs with a mass in the range from $\sim 10^{-1}\ M_\odot$ to $\sim 10^{-3}$ $M_\odot$ constrained as a dark matter candidate if the brown dwarfs formed relatively recently.

3. ESTIMATED OBSERVING TIMES FOR *SIRTF*

3.1. *Individual Brown Dwarfs in the Solar Vicinity*

The 1 σ sensitivity for instruments on *SIRTF* are expected to be ~ 10 μJy at 10 μm and ~ 100 μJy at 60 μm in 500 s of integration (Werner & Eisenhardt 1988).

Consider observing L fields with *SIRTF*, each for a time $t_{\rm pf}$, so the total observing time is $t_t = L t_{\rm pf}$. The 3 σ sensitivity per field is

$$f_{\rm pf}(10\ \mu{\rm m},\ 60\ \mu{\rm m}) \simeq (30\ \mu{\rm Jy},\ 300\ \mu{\rm Jy})\sqrt{500\ {\rm s}/t_{\rm pf}}$$

for observations at 10 and 60 μm, respectively. The expected number of detections per field $N_{\rm pf}$ may be obtained from equation (17) with $\chi = \chi_{\rm pf}$ relevant for the instruments on *SIRTF*; recall that χ, defined in § 2.2, is the solid angle in units of 4π steradians. The total number of detections is $N_t = L N_{\rm pf}$.

Realistically, the search should aim to detect a significant number of brown dwarfs, say 100, so $N_t \simeq 100$. The detector area for the wide-field camera on *SIRTF* is estimated to be ~ 49 square arcminutes (Werner & Eisenhardt 1988), hence $\chi_{\rm pf} \simeq 3.3 \times 10^{-7}$. Given these values equation (17) may be used to estimate the requisite sensitivity per field.

It is straightforward to show that the total observing time t_t is smallest when the number of fields L is largest, assuming that background photons dominate the count rate. This follows since $t_{\rm pf} \propto f_{\rm pf}^{-2}$, so $t_{\rm pf} \propto (\chi_{\rm pf}/N_{\rm pf})^{-4/3}$. The total observing time $t_t = L t_{\rm pf}$ and $N_t = L N_{\rm pf}$; hence, given that N_t and $\chi_{\rm pf}$ are fixed, $t_{\rm pf} \propto L^{-4/3}$, and $t_t \propto L^{-1/3}$. Therefore, as L increases the total observing time decreases given that the detector has a fixed area and that the search aims to detect some number N_t of brown dwarfs. Hence, the total observing time is a minimum when many fields are observed, each for a short time. This also makes subtraction of extraneous radiation fields less problematic, and means that blank field regions of pointed observations can be used to search for individual brown dwarfs in our Galaxy.

The total observing time required to observe 100 brown dwarfs ($N_T \simeq 100$) with a detector such as that on *SIRTF* ($\chi_{\rm pf} \simeq 3.3 \times 10^{-7}$) is $t_t = L t_{\rm pf}$ where

$$t_{\rm pf} = 500\ {\rm s}\left[\frac{f_\nu({\rm per\ field})}{f_\nu({\rm limit\ in\ 500\ s})}\right]^{-2} . \tag{20}$$

The 3 σ flux limit obtained in 500 s at 10 μm is ~ 30 μJy; observations at 10 μm constrain the fraction of the halo dark matter comprised of brown dwarfs with an age of $\sim 10^{10}$ yr and a mass of $\sim 3 \times 10^{-2}\ M_\odot$. The flux limit per field may be obtained from equation. (17) with $\chi = \chi_{\rm pf}$, $N = N_{\rm pf} = N_t L^{-1}$, $\lambda_{\rm max} = 10$ μm, $t_{10} = 1$, and $\kappa_{-2} = 1$; the result is $f_{\rm pf} \simeq 0.16 L^{2/3}$ μJy. Assuming that 500 s of integration is required to reach 30 μJy at 10 μm, the observing time per field is $t_{\rm pf} \simeq 1.7 \times 10^7 L^{-4/3}$ s; hence the total observing time is $t_t = L t_{\rm pf} \simeq 1.7 \times 10^7 L^{-1/3}$ s.

If the observing time per field is about 10^3 s ($t_{\rm pf} \simeq 10^3$ s), then $\sim 10^3$ fields ($L \simeq 10^3$) must be observed. In this case the total observing time required to detect ~ 100 brown dwarfs each with a mass of $\sim 3 \times 10^{-2}\ M_\odot$ is ~ 11.6 days; if some fraction $f_{\rm hm}$ of the 100 are detected then brown dwarfs with a mass of $\sim 3 \times 10^{-2}\ M_\odot$ must comprise $\sim f_{\rm hm}$ of the mass of the dark halo. A total observing time of ~ 12 days is reasonable because the field of view of the wide-field camera is quite large, and the blank field regions (i.e., off-target areas) from pointed observations can be used to search for brown dwarfs. It will be important to know the spectral energy distributions of candidate objects, so observations on each field should be carried out at several wavelengths.

The prospects to detect dwarfs at 60 μm are less bright. Consider the detection of 10 ($N_t = 10$) brown dwarfs which emit primarily at 60 μm, so that brown dwarfs with masses of $\sim 3 \times 10^{-3}\ M_\odot$ (see eq. [6]) will be constrained or detected. At 60 μm a 3 σ flux limit of ~ 300 μJy can be obtained in ~ 500 s.

The limit per field may be obtained from equation (17) with $N = N_{\rm pf} = L^{-1} N_t$, $\chi = \chi_{\rm pf} \simeq 3.3 \times 10^{-7}$ (applicable to *SIRTF*), $\lambda_{\rm max} \simeq 60$ μm, $t_{10} = 1$, and $\kappa = 1$. The result is $f_{\rm pf} \simeq 0.075 L^{2/3}$ μJy. This implies that the integration time per field be $t_{\rm pf} \simeq 8.2 \times 10^9 L^{-4/3}$ s. If the integration time per field is about 10^3 s, then $\sim 1.5 \times 10^5$ fields must be observed. The total observing time is ~ 5 years!

Detectors may have different areas or reach different flux limits in 500 s of integration than has been assumed above. The

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observing time per field and the total observing time to detect a set number of brown dwarfs scale as $t_t \propto t_{\rm pf} \propto (\chi_{\rm pf})^{-4/3} f_{500}^2$.

3.2. *Integrated Halo Emission from a Nearby Galaxy*

The primary signature of the integrated emission from brown dwarfs which comprise the halo dark matter of a nearby galaxy is the spatial distribution of the emission; this will allow emission associated with the halo population to be distinguished from that produced by dust or stars that are not associated with the halo population. It is important, therefore, that the observations allow a density profile to be determined. When the diameter and area of the galaxy are less than those of the detector, the data may be divided into annuli, and data from each annuli combined, as discussed in § 2.1.1. In this case, if the halo emission can be detected at all, the density profile can be determined, as shown in § 2.1.1. Therefore, it is important to choose a galaxy with an angular size, and hence distance, such that the entire dark halo falls onto the detector. Requiring that all areas of the halo of the galaxy be observed simultaneously also will allow for easier subtraction of extraneous radiation fields, such as zodiacal and galactic cirrus emission, since spatial and temporal variations in these radiation fields will be more well defined.

The wide-field instrument on *SIRTF* is expected to have a size of $\sim 7'$. The diameter of the halo of a nearby galaxy is ~ 100 kpc. The dark halo of a galaxy at a distance of ~ 50 Mpc will have an angular diameter of $\sim 7'$. Given that the data from each annuli will be combined as described in § 2.1.1, equation (11) can be used to estimate the requisite sensitivity per pixel. Using this relationship, and assuming $x \simeq 50 R_{50}, t_{10} \simeq 1$, and $\kappa_{-2} \simeq 1$, the flux limit per pixel obtained from equation (11) is $\alpha \lesssim 35 f_{\rm hm}\, \theta_{\rm arcmin} R_{50}^{-2} (\lambda_{\rm max}/23\ \mu{\rm m})^{-0.9}\ \mu$Jy, where $f_{\rm hm}$ is the fraction of the halo mass comprised of brown dwarfs with a blackbody spectrum that peaks at $\lambda_{\rm max}$ (see § 2.1). Given that the detector has P pixels, the angular size per pixel is $\sim \theta_{\rm arcmin} \sim 7/P^{1/2}$. Hence, the requisite flux limit per pixel is $\alpha \lesssim 2.4 f_{\rm hm} P_4^{-0.5} R_{50}^{-2} (\lambda/23\ \mu{\rm m})^{-0.9}\ \mu$Jy, where the number of pixels is $P = 10^4 P_4$.

Brown dwarfs with an age of $\sim 10^{10}$ yr and mass of $\sim 3 \times 10^{-2}\ M_\odot$ emit primarily at $\sim 10\ \mu$m (see eq. [6]). At this wavelength the sensitivity per pixel must be $\sim 5 f_{\rm hm}\ \mu$Jy for $P_4 \simeq 1$, and $R_{50} \simeq 1$. At this wavelength a sensitivity of $\sim 10\ \mu$Jy is reached in ~ 500 s (Werner & Eisenhardt 1988); hence $f_{\rm hm} \sim 0.1$ can be reached in ~ 2.2 days of integration, assuming that the count rate is dominated by background counts.

At 60 μm, relevant for 10^{10} yr old brown dwarfs with a mass of $\sim 3 \times 10^{-3}\ M_\odot$, the prospects for the detection of the halo appear to be zero. A sensitivity of $\sim 0.1\ \mu$Jy is required to detect or limit $f_{\rm hm}$ to be less than ~ 0.1; this would require greater than a year of integration time!

3.3. *Observing Strategies*

It appears that the best way to look for brown dwarfs is to search for individual brown dwarfs in the solar vicinity, using blank field regions of pointed observations. If a population of candidate objects is detected then, assuming that a similar population comprises the halo dark matter of other galaxies, a nearby galaxy could be observed at the appropriate wavelengths to ascertain whether the brown dwarfs have the expected density profile.

The observing times required to detect or constrain a brown dwarf population contributing to the halo dark matter are long. Observations at a given wavelength will constrain or detect brown dwarfs with a given mass, assuming that the dwarfs are old, $\sim 10^{10}$ yr. Observations at 10 μm will constrain the fraction of the halo mass $f_{\rm hm}$ comprised of brown dwarfs with a mass of $\sim 3 \times 10^{-2}\ M_\odot$.

Blank field regions of pointed observations may be used to search for individual brown dwarfs in the solar vicinity that are associated with the halo dark matter. The interesting limit of $f_{\rm hm} \sim 1\%$ for brown dwarfs with a mass of $\sim 3 \times 10^{-2}\ M_\odot$ could be reached in about a month using *SIRTF*. This is a reasonable observing time because the blank field regions of targeted observations can be used to search for brown dwarfs (see § 3.1). If a brown dwarf population were detected, the halo of a nearby galaxy could be observed to confirm that a population of sources emitting at $\sim 10\ \mu$m is contributing to the mass of the dark halo. The primary signature indicating that the halo population has been detected is the radial profile of the halo emission. Given that brown dwarfs with a mass of $\sim 3 \times 10^{-2}\ M_\odot$ comprise $\sim 10\%$ of the halo dark matter, the halo of a galaxy at a distance of ~ 50 Mpc could be detected in ~ 2.2 days of integration.

Another way that the data may be culled to search for the infrared emission produced by a brown dwarf halo is to combine the data for many galaxies; perhaps brown dwarf emission from the summed "galaxy" dark halo will become apparent.

4. SUMMARY

The dark matter that comprises the massive halos of galaxies and the dark matter in clusters of galaxies may be in the form of brown dwarfs. Several ways to detect or constrain the infrared emission from brown dwarfs have been investigated. Brown dwarfs in the following environments could be detected: the integrated infrared emission from brown dwarfs in a nearby galaxy or cluster of galaxies (§ 2.1, § 2.1.1, § 3.2, and § 2.1.2); the infrared emission from individual brown dwarfs in the vicinity of the solar system (§ 2.2 and § 3.1); and the integrated infrared emission from young and old brown dwarfs in a distant galaxy or cluster of galaxies (§ 2.3).

A pointed infrared telescope can be used to detect or significantly constrain brown dwarfs as comprising the halo dark matter by observing a nearby galaxy (§ 2.1 and § 3.2). A survey that covers a significant fraction of the sky, or which covers a small region to a great depth, can be used to detect or significantly constrain brown dwarfs as a halo dark matter candidate by looking for individual brown dwarfs in the solar vicinity (§ 2.2 and § 3.1). The observing times required to detect or constrain such a halo population of brown dwarfs with an instrument such as *SIRTF* are discussed in § 3.

Brown dwarfs in the mass range from $\sim 10^{-1}$ to $10^{-3}\ M_\odot$ with an age of $\sim 10^{10}$ yr radiate predominately at wavelengths from ~ 1 to 150 μm. The brown dwarfs are faint, but could be detected or constrained by *ISO* or *SIRTF*. The observations must be made at several wavelengths so that the colors of sources or of diffuse emission, or limits on colors, can be used to distinguish stellar emission and dust emission from brown dwarf emission.

To directly image the halo of a nearby galaxy, surface brightness limits of less than ~ 30 Jy sr^{-1} at 140 μm and 700 Jy sr^{-1} at 4 μm are required (see Tables 1 and 2 and § 2.1). If the entire halo region is observed and the data from many pixels combined, then the flux limit per pixel can be increased (§ 2.1.1).

Another way to detect or constrain brown dwarfs as a halo dark matter candidate is to search for individual brown dwarfs in the solar vicinity. A survey which covers an area of a few square degrees to flux levels of ~ 100 μJy (at a few μm) to ~ 1 μJy (at 150 μm) should detect or significantly constrain old (10^{10} yr) brown dwarfs in the mass range from $\sim 10^{-1}$ to 10^{-3} $M_\odot$. Alternatively, a survey which covers a large fraction of the sky to flux levels of ~ 45 mJy (at 4 μm) to ~ 400 μJy (at 150 μm) would detect or significantly constrain brown dwarfs as a halo dark matter candidate (§ 2.2).

Galaxies and cluster of galaxies at redshifts of ~ 2 could be detected as strong infrared sources if the dark matter in these is comprised of brown dwarfs, and if the brown dwarfs are relatively young, $\sim 10^8$–10^9 yr.

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