ABSTRACT
I discuss the possibility that a significant fraction of the extremely common faint submm sources found in recent surveys are not in fact high redshift galaxies, but actually local objects emitting only in the submm, with a temperature around 7K. The majority of faint SCUBA sources clearly really are distant galaxies. However if even a quarter or a third of the SCUBA sources are actually local objects, the cosmological implications are significant, as this would selectively remove the objects believed to be at $z > 3$. Two hypotheses - very cold brown dwarfs, and outer solar system bodies - are easily rejected. A third hypothesis - cold dark dusty gas clouds - is not so easily dismissed. I show that the observational constraints on such a population - dynamical limits on local missing matter, the FIR-mm background, and the absence of gross high-latitude extinction features - constrains the mass of such objects to be in the mass range 0.1 to 10 Jupiter masses. On the assumption of virial equilibrium, their sizes are in the range $1 - 100$ AU, with angular sizes around a tenth of an arcsecond. They would be completely opaque at visible and IR wavelengths. The characteristics deduced are closely similar to those of the objects proposed by Walker and Wardle (1998) to explain “extreme scattering events” in quasar radio light curves, and which they propose fill the Galactic halo and explain halo dark matter. Indeed, at around 1 Jupiter mass, the local population density would be similar to that in dark halo models. However, such objects, if they explain a large fraction of the SCUBA submm sources, cannot extend through the halo without greatly exceeding the FIR-mm background. Instead, I deduce the characteristic distance of the SCUBA sources to be around 100 pc, consistent with being drawn from a disk population with a scale height of a few hundred parsecs. Possibly a “Population II” dust-less version of such objects could exist in the halo. Regardless of the dark matter problem, the possible existence of such compact sub-stellar but non-degenerate objects is intriguing. Such objects should collapse on a very short timescale, but at such a low temperature it is possible that cosmic ray heating can maintain them in equilibrium. The main theoretical objection is that such an equilibrium may be unstable on a thermal timescale. If however such objects do exist, they may be seen as “failed stars”, representing an alternative end-point to stars and brown-dwarfs. It is possible that they greatly outnumber both stars and brown dwarfs. The nearest such object could be a fraction of a parsec away. Several relatively simple observations could critically test this hypothesis.
1 Introduction

Deep submm surveys of small patches of sky have only just become feasible, largely due to the development of the SCUBA instrument on the James Clerk Maxwell Telescope (Holland et al 1999). Several groups have pursued surveys on scales of a few arcminutes to mJy levels (Smail, Ivison, and Blain 1997; Hughes et al 1998; Barger et al 1998, 1999; Eales et al 1998; Lilly et al 1999; Blain et al 1999a), finding a very large sky density of faint submm sources. These surveys seem to have justified the long held belief that submm surveys would be a short-cut to the high-redshift universe, as the so-called “negative k-correction” effect largely counterbalances the dimming due to distance and redshift, so that objects can be seen just as easily at very high redshift \( (z = 3 - 10) \) as they can at moderate redshift \( (z \sim 1) \). High redshift optical identifications have indeed been proposed for many of the submm sources in the above papers. The IR-mm luminosities of the sources are then very large, similar to local ultraluminous IRAS galaxies, with implied star formation rates of hundreds of solar masses per year. However, given the sky density of these sources, the high redshift luminosity density must be large. Hughes et al (1998), in their study of submm sources in the Hubble Deep Field (HDF), show that the implied star formation rate at \( z = 2 - 5 \) is larger than that deduced from the UV fluxes of all the optically selected high-z galaxies in the HDF. The optically derived star-formation history curve, or Lilly-Madau plot, has since undergone revision but the qualitative point remains unchanged. This has striking consequences - most of the star formation in the young universe was obscured, and most of the star formation in the young universe went on in a tiny minority of starburst galaxies, not in the great majority of quiescent or moderately active objects. This is quite the reverse of the situation today. There may be problems with such a picture - Blain et al (1999a) show that a star-formation history of the kind deduced by Hughes et al may, over the history of the universe, overproduce the metals, and overproduce the number of observed stars.

It may very well be that the above story is broadly correct, but it is so important that we must make sure that we have excluded reasonable alternatives. One such alternative is that some fraction of the submm sources are actually AGN rather than starbursts (Almaini Lawrence and Boyle 1999; McMahon et al 1999; Fabian et al 2000; Gunn et al in preparation). Another more radical alternative is that the submm surveys, like all other first surveys of the sky at a new wavelength, are discovering a new class of object. We are driven to examine such an idea because the optical identifications of submm sources with high redshift galaxies, while highly plausible, are often only circumstantial. The problem of course is the large beam size of SCUBA \( (14'' \) so that identifications are nearly always ambiguous. In some cases, a relatively bright galaxy is within the error circle, and so statistically secure. But these are the less interesting cases - reasonably secure identifications at \( z \sim 0.5 - 1 \). In some other cases, identifications in the range \( z \sim 1 - 3 \) are secure because of confirming CO detections, or because of the presence of extremely red objects (EROs) which are relatively rare (Ivison et al 1998; Frayer et al 1998, 1999; Smail et al 1999). In a large number of cases however, several faint blobs are positionally consistent, and the identification rests on the constraints given by limits on the spectral energy distribution (SED) - for example non-detection at 15\( \mu \)m in the ISO data together with a detection at 850\( \mu \)m ruling out objects with an ARP 220-like SED at low redshift (see Hughes et al 1998), or the submm/radio ratio (Carilli and Yun 1999; Blain 1999). In all such cases, the submm source is equally consistent with having no optical counterpart at all.

For the brightest SCUBA sources, mm-wave interferometry is just feasible and can of course substantially increase locational accuracy. Downes et al (1999) observed HDF 850.1, the brightest SCUBA source in the HDF, with IRAM, and achieved a position accurate to 0.3''.

Within the 2\( \sigma \) contour, there is no object at all to the limit of the HDF. Two very faint
objects are consistent at 3\(\sigma\). However, the tentative photometric redshifts of those objects are inconsistent with the SED of HDF 850.1, if the intrinsic SED is like that of ARP 220 or M82 (Hughes et al. 1998). There are several possible explanations. (i) It could be that the intrinsic SED is different from those classic exemplars, and indeed Downes et al. find a local object whose SED does appear to be consistent. (ii) It could simply be that the tentative redshifts are wrong. (iii) The most interesting possibility is that the correct identification is at very high redshift, \(z > 5\). The combination of distance dimming, k-correction, and some reddening could move such an object out of the detection limit for the HDF. Deep K-band imaging by Smail et al. (1999) has shown that perhaps 10% of the SCUBA sources are “Extremely Red Objects (EROs)”, appearing only in the IR. Unpublished deep K-band imaging of the CFRS survey sources show that only one third appear to identified, even to \(K = 21.5\), suggesting that most counterparts are at \(z > 2\) (Eales, private communication).

In some ways the simplest explanation for the non-identification of HDF 850.1 is that it is an object that is bright in the submm but emits negligible light at optical wavelengths. Is it possible that such a previously unsuspected population of objects exists, and at such a high sky density? We must at least discount such a hypothesis before believing the consequences of submm surveys for cosmology. In this paper I consider three such possible populations and test them against the constraints we have. The first two - brown dwarfs and solar system objects - are quickly dispensed with. The third hypothetical population examined - very cold dense dark dust clouds - turns out to be much harder to dismiss, as long as the clouds are in the sub-stellar mass range. Furthermore such objects may plausibly contribute substantially to the dark matter problem, as has been suggested by other authors for quite different reasons (Pfenniger Combes and Martinet 1994; Gerhard and Silk 1996; Walker and Wardle 1998). Once we have arrived at the concept of such objects, they seem more than plausible, as a likely end-product of cloud collapse, and as an alternative to brown dwarfs. Even if they do not turn out to constitute a large fraction of the SCUBA sources, it is of some interest to discover whether they exist at all.

2 Observational constraints

Any model aiming to explain the sub-mm sources must satisfy a substantial number of constraints. (i) The objects must have an SED consistent with what we know from the brighter submm sources. (ii) Their distribution on the sky must be at least grossly isotropic, although current surveys cannot exclude variations of the order of tens of percent. (iii) The deduced space density must not exceed the limits imposed by local dynamics. (iv) Their integrated surface brightness must not exceed the FIR-mm background discovered by COBE. (v) The population covering factor must be small, or the objects would already have been discovered through extinction effects. Most of these constraints will be revisited as we proceed, but I now look at two of the key constraints more carefully, followed by a brief discussion of the possible importance of radio emission.

2.1 Temperature constraint from the SED of HDF 850.1

To constrain the SED, I have taken HDF 850.1 as the exemplar, as it has no identification, but has been measured at a number of wavelengths. Table 1 lists the reported fluxes and limits for HDF 850.1. Table 2 takes various ratios and for each lists the range of temperatures consistent with the ratio concerned, for (a) a blackbody SED, (b) a greybody SED with various values of \(\beta\). Here the greybody form is defined as usual as a spectrum with the form \(F_\nu = Q_\nu B_\nu(T)\) where \(Q_\nu \propto \nu^\beta\). The limits and ranges discussed below are
all effectively at approximately 95% confidence.

The crucial ratio is \( S(450\mu m)/S(850\mu m) \). This has an effective power-law slope \( \alpha < 1.2 \), much flatter than a Rayleigh-Jeans slope, telling us that whether blackbody or greybody, the objects must be extremely cold - blackbodies must be colder than 18K, and greybodies colder than 9K. The long wavelength ratios are also interesting. The ratio \( S(1300\mu m)/S(850\mu m) \) has an effective power law slope of \( \alpha = 2.7 \pm 0.4 \), favouring a greybody interpretation but not quite ruling out a blackbody. The ratio \( S(2800\mu m)/S(1300\mu m) \) implies a power law slope of \( \alpha > 2.3 \), formally ruling out blackbody emission. Given the likely systematic errors on these fluxes, we cannot be confident of this conclusion, but a greybody is clearly preferred.

Overall, blackbody emission is mildly ruled out, and must in any case be colder than 18K. For greybody emission, we cannot separate variations in \( \beta \) and \( T \), but for a given \( \beta \) the implied \( T \) is very tightly constrained. For \( \beta \) anywhere within the normally considered range for Galactic dust (\( \beta \sim 1 - 2 \)), the total allowed range of temperature is \( T = 4.7 - 9.4 \). For much of this paper, I take \( T = 7 \) as the best-bet temperature value.

Most other blank field survey SCUBA sources have so far been measured only at a single wavelength, 850\( \mu m \). They are generally too faint to detect at 450\( \mu m \). However Eales et al (2000) have co-added the 450\( \mu m \) data at the position of their 850\( \mu m \) sources, and find that the mean value of the flux ratio at these two wavelengths is \( S(450)/S(850) < 1.9 \), at 3\( \sigma \) confidence. For a variety of reasons discussed in their paper, there may systematic uncertainties in this analysis, so that the true ratio could be as large as 3. However it is clear that HDF 850.1 is at least not unusual, and it is even possible that most sources are even colder.

### 2.2 Limits on space density of any unknown population

It is possible that the kinds of objects we will consider are indeed submm sources and of astrophysical interest, but we are primarily concerned with whether such objects are common enough to explain a substantial fraction of the sources in the blank field surveys. The number counts from submm surveys still have considerable uncertainty, but down to \( S(850\mu m) = 2 \) mJy the surface density of sources is \( N \sim 2000 - 3000 \) deg\(^{-2} \), i.e. a source every arcminute or two (Hughes et al 1998; Blain et al 1999a; Barger, Cowie and Sanders 1999). If any new population is to be significant, then it must have let us say \( N \sim 1000 \) deg\(^{-2} \) at a flux of 2 mJy. This surface density will be taken as a reference point in everything that follows. If we postulate a population of objects with a given luminosity, we can calculate the distance \( D \) to which they are detectable to 2 mJy. If we further assume a mass \( M \) for the objects, then we can deduce the overall mass density of the population, \( \rho = 3MN/D^3 \).

In the solar neighbourhood we now have a reasonably agreed census for both stars and interstellar matter, and in addition have an estimate of the dynamical mass from vertical motions of stars (see eg Binney and Merrifield 1999 and references therein; and the most recent determinations from Creze et al (1998) and Holmberg and Flynn (2000). The local dynamical mass and the observed material are in quite good agreement at around \( \rho \sim 0.1M_\odot \) pc\(^{-3} \). Of this, roughly 45% is in stars and remnants, and 55% in gas. The uncertainties are still significant, but a fairly robust conclusion is that any hitherto undetected component in the solar neighbourhood cannot have a density greater than \( \rho \sim 0.03M_\odot \) pc\(^{-3} \). Note however that this limit is still quite consistent with the likely local contribution from halo dark matter; a variety of models is still consistent with the data, but a solar neighbourhood normalisation of around \( \rho \sim 0.01M_\odot \) pc\(^{-3} \) is quite typical (eg Alcock et al 1996; Evans 1996).
2.3 Possible radio emission

Although the IRAM position of HDF 850.1 coincides with no optical counterpart, there is a marginally significant and extremely faint radio source which, if indeed real, is nicely consistent with the position of the submm source. (See Figure 4 of Downes et al). The ratio $S(850\mu m)/S(3.5\text{cm}) \sim 900$, some two orders of magnitude larger than that seen in local starburst galaxies, but quite possibly consistent with that expected from a highly redshifted starburst (Carilli and Yun 1999; Blain 1999). At lower frequency the source is not detected, so that $S(850\mu m)/S(20\text{cm}) > 300$. Smail et al (2000) found faint radio counterparts to 7/15 SCUBA sources that they surveyed, with nearly all of these being the brightest submm sources and/or those with reasonably secure optical counterparts. The mean flux ratio for the detections was $S(850\mu m)/S(20\text{cm}) \sim 140$, consistent with tentative redshifts in the range $z=1-3$. Including the undetected sources, Smail et al state that a conservative value for the median redshift is $z \geq 2.5$. Another deep radio study, of the CFRS survey SCUBA sources, detected 5/19 objects (Eales et al 2000). The majority of the faintest SCUBA sources are therefore either at very high redshift ($z>3$) or are simply not radio sources, or at least extremely feeble ones.

In summary, it may be that there is no effect to explain, but potentially the existence of, albeit extremely weak, radio emission is a difficult challenge to local hypotheses for the SCUBA sources. We return to this question in section 5.6.

3 Brown Dwarfs

Brown dwarf candidates discovered in the last few years are bright IR sources but optically faint, with temperatures of the order 1000K. Is it possible there is a large population of low mass and/or very old sub-stellar degenerate objects that are completely invisible at optical wavelengths? Presumably their gross SED would be at least approximately blackbody, which may be ruled out in the case of HDF 850.1. More importantly, current brown dwarf models (Burrows et al 1997) find that even for Jupiter sized objects that are as old as the Galaxy, the expected temperature is still of the order 90K, quite inconsistent with the observed SED of HDF 850.1. Even ignoring this problem, we can soon see that the population can only be seen very close by, and would have an absurdly large space density. Scaling to the radius of Jupiter ($R_J$), we can estimate the distance at which such an object would have an $850\mu m$ flux of 2 mJy:

$$D(\text{pc}) = 0.018 \times \left(\frac{R}{R_J}\right) \left(\frac{T}{10}\right)^{1/2} \left(\frac{F}{2\text{mJy}}\right)^{-1/2}$$

I have assumed blackbody radiation at $T \sim 100K$, and taken the Rayleigh-Jeans approximation. If we now assume a mass $M$ for each object, also scaled to the Jupiter value $M_J$, then for a sky density of $N = 1000$ deg$^{-2}$ we get an overall population space density

$$\rho(M_\odot\text{pc}^{-3}) = 1.63 \times 10^9 \times \left(\frac{M}{M_J}\right) \left(\frac{R}{R_J}\right)^{-3} \left(\frac{T}{10}\right)^{-3/2} \left(\frac{F}{2\text{mJy}}\right)^{3/2} \left(\frac{N}{1000}\right)$$

We conclude that a population of brown dwarfs cannot explain the majority of the SCUBA sources. If such very old small brown dwarfs do exist at a temperature of $T \sim 100K$, then
at a flux level of 2 mJy there can only be a handful over the whole sky without violating the local mass density limit.

Examining the above equation, we can see that the escape route is that for a given mass one wants a much larger radius. To be consistent with local density limits, Jupiter mass objects would need to be a few AU in size. We examine this possibility shortly. But first, another possibility is to find a locality where the density might just be that high - inside the solar system.

4 Trans-Neptunian Objects

In recent years wide field searches have discovered that there is a substantial population of asteroid-sized bodies beyond Neptune (eg review by Weissman 1995). These are often referred to as “Kuiper Belt Objects” although their latitude and orbit distribution is not yet well known. Beyond this, it has of course been long postulated that there is a vast population of icy bodies which acts as the reservoir for comets (i.e. the “Oort Cloud”), perhaps as many as $10^{13}$ objects out to 30,000 AU. This is of course more than enough sky density but we are unlikely to detect objects that far. If we assume an albedo of 0.1 (typical of comets) then at a distance $D$ solar heating leads to a temperature $T_{ss} = 38.5 \left( \frac{D}{100 \text{AU}} \right)^{-1/2}$.

Here I have used the “sub-solar temperature” appropriate to the surface facing the sun, as this is also the face that radiates back toward us. To be as cold as $T \sim 7\text{K}$ the object would need to be at a distance of $\sim 3000$ AU. To have a submm flux of 2 mJy an object would then need a size of around 70,000 km, i.e. such objects would be of roughly Jupiter size. If the sky density is as large as $N = 1000 \text{deg}^{-2}$, then the total mass in such objects would be of the order of $10^4 M_\odot$ - unlikely not to have been noticed. If we put aside the temperature constraint and just calculate the submm flux, then we find that an object of radius $R$ would be detectable to a distance given by

$$\left( \frac{D}{100 \text{AU}} \right) = 1.01 \times \left[ \left( \frac{R}{1000 \text{km}} \right)^2 / \left( \frac{F}{2 \text{mJy}} \right) \right]^{2/5}$$

Thus a Pluto sized object ($\sim 1000$ km) could be seen to $\sim 100$ AU, whereas an asteroid sized object ($\sim 100$ km) could be seen to $\sim 16$ AU. This roughly matches the size and distance range of the trans-Neptunian objects seen so far, to limiting magnitudes around $V \sim 25$. Such known TNOs should then be just visible to SCUBA. However, the surface density of objects to $V\sim 25$ is $\sim 10 \text{deg}^{-2}$, so they fail to explain a significant fraction of SCUBA sources by around 2 orders of magnitude. The final blow is that at such distances objects still have significant parallactic motion. (This is after all how they have been discovered). Even at 100 AU the expected motion is $32''$ per day. However the 2mJy depth achieved by Hughes et al. (1998) in the HDF required 50 hours of integration spread over many separate observing nights.

I conclude that outer solar system bodies cannot explain a significant fraction of discrete SCUBA sources. It remains possible of course that the integrated emission contributes
to the FIR background. However Dwek et al. (1998) go through similar calculations and conclude that solar system objects are not a significant contributor to the background.

5 Cold Dark Clouds

We know of course that cold dark clouds exist in the Galactic plane, and they emit strongly in the submm. The question here is whether they can be small enough, cold enough, and common enough (at high as well as low galactic latitudes) to explain the population of discrete SCUBA sources. I consider clouds of mass $M$, with gas-to-dust ratio $\mu$, emitting in the submm by optically thin grey-body emission from dust particles at temperature $T$. (In a later section I check the optically thin assumption, find that it may be invalid for some of the mass range considered, and repeat some of the key calculations assuming blackbody emission). The mass of dust can be computed from the observed flux in the usual way from

$$M_d = \frac{F_\nu D^2}{K_d(\nu)B_\nu(T)}$$

Here $D$ is the distance of the cloud, $B_\nu(T)$ is the Planck function, and $K_d(\nu)$ is the usual dust emission coefficient, $K_d(\nu) = 3Q_\nu/4a\rho$, where $Q_\nu$ is the dust emissivity, $a$ is the grain radius, and $\rho$ the grain density. For a wavelength of 850$\mu$m, we use $K_d = 0.14$ (see for example Hughes, Dunlop, and Rawlings 1997).

5.1 Distance and space density

We can now calculate the distance at which a cloud of given mass will have a flux of 2 mJy. I quote the result scaled to a Jupiter mass, as we shall see shortly that this is the relevant mass scale. The distance derived is proportional to the square root of the Planck function. A little numerical experimentation shows that at a wavelength of 850$\mu$m an approximation accurate to 10% over the range $2 - 12K$ is $\sqrt{B_\nu(T)} \propto (T - 2)/5$. I use this approximation to show the effect of varying the assumed temperature, normalised to a value of $T = 7K$. The result is

$$D(\text{pc}) = 94 \times \left( \frac{M}{M_J} \right)^{1/2} \left( \frac{\mu}{100} \right)^{-1/2} \left( \frac{T - 2}{5} \right) \left( \frac{F}{2\text{mJy}} \right)^{-1/2}$$

Given this result, there are two appealing mass scales. For $M \sim 10^4 M_J \sim 10M_\odot$ the clouds would be at 10kpc, and could thus be a halo population and so isotropic. At $M \sim M_J$ the characteristic distance is of the order 100 pc. Such objects could then a disk population, but are close enough to be approximately but not precisely isotropic. (Of course fainter objects could be further away, but in section 5.2 we show that in fact the population cannot extend much further). If we now assume that the population to this distance has surface number count $N = 1000 \text{deg}^{-2}$ we can calculate the implied mass density

$$\rho(M_\odot \text{pc}^{-3}) = 0.011 \times \left( \frac{M}{M_J} \right)^{-1/2} \left( \frac{\mu}{100} \right)^{3/2} \left( \frac{F}{2\text{mJy}} \right)^{3/2} \left( \frac{T - 2}{5} \right)^{-3} \left( \frac{N}{1000} \right)$$
If the implied density is to not to exceed the limit on previously undetected material \( \rho = 0.03 \) then we find that \( M > 0.1 M_J \). Thus extremely small objects are excluded. If \( M \sim M_J \) the implied density is approximately equal to the expected local density of the dark halo, leading to the intriguing possibility that SCUBA sources are the famous dark matter. If \( M >> M_J \) the objects concerned are still of great interest, but not dynamically significant, and not a major component of the interstellar medium in mass terms.

The number density of our objects, \( n = \rho / M \) is found to be:

\[
\begin{align*}
n(\text{pc}^{-3}) &= 11.9 \times \left( \frac{M}{M_J} \right)^{-3/2} \left( \frac{\mu}{100} \right)^{3/2} \left( \frac{F}{2\text{mJy}} \right)^{3/2} \left( \frac{T - 2}{5} \right)^{-3} \left( \frac{N}{1000} \right) \\
&\quad \text{if the objects are massive (e.g. } M \sim 10 M_\odot \sim 10^4 M_J \text{) then they are fairly sparse. However if the objects are small (} M \sim M_J \text{) then they are an order of magnitude more common than stars. While the typical 2 mJy SCUBA source may be 100 pc away, the nearest object may be only half a parsec away and as bright as 10 Jy.}
\end{align*}
\]

5.2 The FIR-mm background and the spatial distribution of the clouds

Taking our fiducial values of \( N = 1000 \text{ deg}^{-2} \) at \( F = 2 \text{ mJy} \), and assuming a simple Euclidean counts model, the summed surface brightness of all sources down to this flux level should be \( I = 0.02 \text{ MJy sr}^{-1} \). This is approximately one seventh of the isotropic background measured by COBE (Fixsen et al 1998). This is not a surprise, as Hughes et al (1998) have already pointed out that the SCUBA sources as whole down to 2 mJy explain about one half of the observed background, and we are working on the hypothesis that the postulated local population is a half or somewhat less of the total SCUBA source population. The crucial implication is that the objects concerned cannot stretch much further in distance than we have already deduced for 2 mJy sources. For high-redshift galaxies, this is really an effect in time, as more distant objects are seen at an early epoch. For our postulated local objects, if we assume that they should contribute no more than say half the background, then, again assuming a Euclidean counts model, the population can extend no further than about 3 times the distance deduced for 2 mJy sources. Whether this is reasonable depends on the mass of the objects.

(i) If our 2 mJy cold dark clouds have \( M \sim 0.1 - 1 M_J \) they are at a distance of \( \sim 30 - 100 \text{ pc} \), and so cannot extend much beyond 100 - 300 pc. However the local stellar disc has a scale height of 300 pc, and the interstellar medium of around 100 pc (Binney and Merrifield 1999). Objects in this mass range are therefore nicely consistent with being a disk population.

(ii) If our 2 mJy cold dark clouds have \( M \sim 1 - 10 M_\odot \sim 10^3 - 4 M_J \) then they are at a distance of \( \sim 3 - 10 \text{ kpc} \), and cannot extend beyond 10 - 30 kpc. This is at least roughly consistent with being a halo population.

These two mass ranges then seem to allow spatial distribution models that are at least reasonable, as either disk or halo objects. We cannot strictly rule out objects with \( 10 - 100 M_J \) or \( M > 10^5 M_J \), but the spatial distributions required are rather arbitrary.

As well as being consistent with the observed intensity of the FIR-mm background, our cold dark clouds should also be consistent with its spectrum. Fixsen et al (1998) found that the spectrum they derived could be well fitted with a grey body functional form, with \( \beta = 0.64 \) and \( T = 18.5 \). They intended this as a parametric description of the data rather than a physical model, and of course an emissivity index \( \beta = 0.64 \) is considerably flatter than the
\[ \beta \sim 1 - 2 \] normally found in both Galactic and extragalactic objects. Dwek et al (1998) model the combined FIRAS-DIRBE data by the FIR emission from star formation over the history of the universe. A redshifted greybody is still a greybody, with \[ \beta \] unchanged but the apparent temperature reduced by a factor \((1 + z)\). The flat observed \[ \beta \] results from the summation of contributions from a wide range of redshifts.

Figure 1 shows how the Fixsen et al spectrum can be decomposed into warm and cold components. I fixed the emissivity index for both components to be \( \beta = 1.3 \), which is the mean value found in a recent submm study of 104 IRAS galaxies (Dunne et al 2000), and is also fairly typical of starburst galaxies (e.g. M82 : Hughes et al 1994). The temperature of the cold component was fixed at \( T_2 = 7K \). There were then two free parameters - the temperature \( T_1 \) of the warm component, and the relative strength of the two components. There are several important features that come out of this analysis. (i) The FIR-mm background can easily accomodate such a very cold component in a natural way. The cold component is similar to that claimed to be seen throughout the Galaxy by Reach et al (1995). (ii) The warm component has a temperature of around \( T_1 \sim 17 \). This is quite consistent with an M82-like starburst spectrum as found by Hughes et al, with \( T \sim 50 \) and \( \beta = 1.3 \) at \( z = 2 \). (iii) The two components cross at about 800 \( \mu m \). Note that this was not fixed in advance by the modelling, but seems to be required to fit the spectrum. Thus at far-IR wavelengths the warm objects (presumed high-z galaxies) dominate; at mm wavelengths the cold objects (postulated here to be cold dark clouds) dominate; but at sub-mm wavelengths they are roughly equally numerous.

Obviously much more careful modelling is needed, using for example a template starburst SED rather than a single temperature greybody, and summing over an assumed star formation history, as Dwek et al (1988) did. Compared to the Dwek et al analysis the effect of adding a very cold component is likely to be (a) requiring a more peaked star formation history, and/or (b) implying a narrower SED, one more like M82 than the Dwek et al template, ARP 220. Finally however we note that both the Fixsen et al (1998) and the Puget et al (1997) derivations of the FIR-mm background required the modelled removal of a Galactic component assumed to be of fixed colour. This should now be seen as an unsafe assumption, so the extragalactic background should really be re-derived self-consistently.

### 5.3 Physical size of clouds

So far I have derived constraints on the allowable mass range based on local density limits and the FIR-mm background. The other strong constraint we want to examine is the covering factor of such objects, for which we need some estimate of their size. This also allows us to consider other interesting physical characteristics such as density and column density, and allows us to check the optically thin assumption.

The sources concerned have been found as point sources in SCUBA maps, and so cannot be very much larger than the SCUBA beam size, \( 14'' \). As they are rather weak sources, it is probably hard to exclude them having diameters of up to say \( 30'' \) across. At the distance derived above for 2 mJy sources, this corresponds to a physical radius of \( R(\text{m}) \leq 2.11 \times 10^{14}(M/M_J)^{1/2} \). For our exemplar HDF 850.1, we can place a tighter limit. Downes et al examine the beam profile and state that the source diameter is less than \( 2'' \). This is consistent with the fact that the 1.3mm flux seen within the IRAM beam of \( 2.1 \times 1.7'' \) is consistent with the flux measured at \( 1350\mu m \) by Hughes et al (1998) with SCUBA, showing that the source is not significantly larger than the IRAM beam. We take this as implying that the angular radius is less than \( 1'' \). The \( 850\mu m \) flux of HDF 850.1 is 7.0 mJy so that its implied distance is 50.2 pc. At this distance the physical size of the source is
How big might we expect such clouds to be? One possible simplifying assumption is that they are in virial equilibrium, which is also the same size (approximately) at which they might be in hydrostatic equilibrium, and at one Jeans mass. The potential energy will be $U = \alpha GM^2/R$ where $\alpha$ depends on density profile. For uniform density, $\alpha = 3/5$. However we expect that the clouds are likely to be isothermal (see section 8) so that $\rho \propto 1/r^2$ which gives $\alpha = 1$. Next we assume that the cloud is almost entirely molecular hydrogen. At a temperature of 7K the rotational levels of $H_2$ will not be excited, so the energy per molecule is $3kT/2$. Finally we arrive at a virial size

$$R_{\text{virial}}(\text{m}) = 1.46 \times 10^{12} \times \left(\frac{M}{M_J}\right) \left(\frac{T}{7}\right)^{-1}$$

For large masses ($> 10^{2-4} M_J$) the observed limits imply a size comparable to the virial size or even smaller, depending on whether one takes the general SCUBA limit or the IRAM limit appropriate to HDF 850.1. For smaller clouds the observed limits allow the clouds to be larger than the virial size. However a cloud above its virial size will collapse on a free-fall timescale, giving a collapse time of $t_{\text{collapse}} \leq 2,000 \text{ years} \times (M/M_J)^{1/4}$. Such objects would soon reach their virial sizes. However we then arrive at a second problem. The thermal energy content of the cloud is roughly $M/2m_p \times 3/2kT$. Its luminosity we can crudely estimate as $\nu L_\nu$ where $L_\nu$ is the monochromatic luminosity for a flux of 2mJy and a distance of 94 pc, with all the usual scalings. We then find that the cooling time is $t_{\text{cool}} \sim 3500$ years, independent of mass. Maintaining such clouds in equilibrium therefore requires a heating source, and it is not obvious whether such an equilibrium would be stable. We return to these problems in section 8, assuming for the while that they can be solved.

Our postulated clouds are extremely dense compared to normal molecular clouds, but still very diffuse compared to stars. A Jupiter mass cloud has a size of 9.8 AU, comparable to the orbital radius of Jupiter. The density, in hydrogen atoms per unit volume, is

$$n_H(\text{m}^{-3}) = 8.72 \times 10^{16} \times \left(\frac{M}{M_J}\right)^{-2} \left(\frac{T}{7}\right)^3$$

The column density is

$$N_H(\text{m}^{-2}) = 2.55 \times 10^{29} \times \left(\frac{M}{M_J}\right)^{-1} \left(\frac{T}{7}\right)^2$$

With standard dust properties, we then expect the optical extinction to be $A_V \sim 13,000(M/M_J)^{-1}$, i.e. the clouds are completely opaque to normal starlight.

### 5.4 Are the clouds optically thin or thick?

Are the clouds optically thin (to their own submm radiation) as I have been assuming? We can check this by calculating the blackbody radiation from a body at $T = 7K$ assuming the virial radius derived above. The ratio of the predicted optically thin dust luminosity to the predicted blackbody luminosity is found to be
For large clouds the optically thin assumption is justified. The smallest clouds we have been considering (\(\sim 0.1 M_J\)) on the other hand are clearly optically thick. They would better be modelled as blackbodies, but in fact as we have seen in section 2.1, a blackbody SED is marginally ruled out. For masses around 1\(M_J\), the correct SED will require radiative transfer to calculate properly, and could for example look like a blackbody at 450\(\mu m\) but a greybody at 1350\(\mu m\). For the remainder of this paper I make the simplifying assumption that the clouds are optically thin at \(M > M_J\) and black-body like at \(M < M_J\). I now recalculate the cloud distance, and local Galactic mass density and number density, for clouds with \(M < M_J\) using the blackbody formula, and assuming the virial size derived above.

\[
\frac{L_{\text{thin}}}{L_{\text{blackbody}}} = 0.40 \times \left(\frac{M}{M_J}\right)^{-1} \left(\frac{T}{7}\right)^2
\]

\[
D(\text{pc}) = 149 \times \left(\frac{M}{M_J}\right) \left(\frac{7T - 2}{5}\right) \left(\frac{F}{2\text{mJy}}\right)^{-1/2} \quad M < M_J
\]

\[
\rho(M_\odot\text{pc}^{-3}) = 0.0028 \times \left(\frac{M}{M_J}\right)^{-2} \left(\frac{5}{2\text{mJy}}\right)^{3/2} \left(\frac{7}{5T - 2}\right)^3 \left(\frac{N}{1000}\right) \quad M < M_J
\]

\[
n(\text{pc}^{-3}) = 2.97 \times \left(\frac{M}{M_J}\right)^{-3} \left(\frac{F}{2\text{mJy}}\right)^{3/2} \left(\frac{5}{7T - 2}\right)^3 \left(\frac{N}{1000}\right) \quad M < M_J
\]

The density has a much steeper mass dependence than before. The main conclusion is that if we are not to exceed the limit on local unseen mass, \(\rho < 0.03\), the mass limit becomes tighter than before: \(M > 0.3 M_J\).

### 5.5 Angular size and covering factor

In the previous section we found that the clouds will be opaque at visible wavelengths. Will they produce extinction effects that should have been previously noticed? Taking our derived virial size and the distance deduced for an object with a flux of 2 mJy, I find an angular radius as follows:

\[
\theta''(\text{arcsec}) = 0.10 \times \left(\frac{M}{M_J}\right)^{1/2} \left(\frac{\mu}{100}\right)^{1/2} \left(\frac{F}{2\text{mJy}}\right)^{1/2} \left(\frac{7}{T}\right) \left(\frac{5}{T - 2}\right) \quad M > M_J
\]

\[
\theta''(\text{arcsec}) = 0.07 \times \left(\frac{F}{2\text{mJy}}\right)^{1/2} \left(\frac{5}{T - 2}\right) \quad M < M_J
\]

The two versions are for the optically thin and optically thick limits respectively. Next we can calculate the covering factor of all sources down to a flux of 2 mJy, assuming a uniform distribution in space, and normalising to surface number counts \(N = 1000 \text{ deg}^{-2}\):
\[ f = 2.5 \times 10^{-6} \times \left( \frac{M}{M_J} \right) \left( \frac{\mu}{100} \right) \left( \frac{F}{2 \text{mJy}} \right) \left( \frac{N}{1000} \right) \left( \frac{T}{5} \right)^2 \left( \frac{T - 2}{5} \right)^{-2} \quad M > M_J \]

\[ f = 1.0 \times 10^{-6} \times \left( \frac{F}{2 \text{mJy}} \right) \left( \frac{N}{1000} \right) \left( \frac{T}{5} \right)^{-2} \quad M < M_J \]

Thus large clouds \((M \sim 10^4 M_J \sim M_\odot)\) would produce extinction features 10″ in size, covering 1% of the sky. This would certainly have been noticed. Small clouds \((M \sim M_J)\) would be a tenth of an arcsec in size, covering only a milliarcsecond of the sky. Historically, such features would easily have been missed, producing occasional indentations in diffuse background light of depth no more than a few percent. In HST imaging however, they might appear as complete black spots, at a frequency of one or two per WFPC2 image. Note that the angular size deduced here is only a crude estimate - as well as the uncertain parameters quoted in the formulae above, the use of virial size is only a first crude guess. We might expect that the angular size is reliable to a factor of a few. The encouraging result then is that we are just within the testable regime. Searching for black spots may heavily constrain or even rule out the model.

The above calculations pertain to sources down to 2 mJy. Above this flux, about once per square degree, we would find a source at 0.2 Jy that produces an extinction feature 1″ across. Somewhere over the whole sky there could be an object 20″ across. Below 2 mJy, the background limit tells us that the clouds could extend up to three times further at high latitude. There might be around five per WFPC2 field, but only 0.02 - 0.03″ across, so that even to HST the spots would not be black.

### 5.6 Passive radio emission

As discussed in section 2.3, it is possible though not certain that blank field submm sources are very faint radio sources, with a submm/radio ratio much larger than for low-redshift starbursts. For our template source HDF 850.1, the marginal detection at 8.6 GHz gives a ratio \(S(850 \mu \text{m})/S(8.6 \text{ GHz}) = 933 \pm 200\), and the upper limit at 1.4 GHz gives \(S(850 \mu \text{m})/S(1.4 \text{ GHz}) \geq 304\). Can cold dark clouds produce weak radio emission? The interstellar medium is of course pervaded by cosmic rays. These produce synchrotron radiation with a volume emissivity \(\epsilon_\nu \sim 2.4 \times 10^{-41} \text{ W Hz}^{-1} \text{ m}^{-3}\) (estimated from Fig 18.15 of Longair (1994)). Synchrotron emissivity scales as \(B^{1+\alpha}\), so perhaps enough radio emission could be produced if the magnetic field in our clouds is significantly enhanced above the ISM average. If the heating of the clouds is by cosmic rays, they will also maintain a steady ionisation level, which could in turn maintain a magnetic field. We have no real way of knowing what this field might be, but try two guesstimates. First, equipartition: if the thermal energy density of the clouds \((n_{H_2} \times 3kT/2)\) comes into equilibrium with magnetic energy density \((B^2/2\mu_0)\) then we find a predicted field \(B_{eq}(\text{Tesla}) = 4.0 \times 10^{-6} \times (M/M_J)^{-1} (T/7)^{3/2}\). Second, if we assume that \(B \propto \sqrt{n}\) as seems to be the case for molecular clouds, we can scale from the average density and magnetic field in the Galactic disk, \(n_H = 3 \times 10^6 \text{ m}^{-3}\) and \(B = 3 \times 10^{-10} \text{ T}\) (see Longair 1994) to find \(B = 5.1 \times 10^{-5} \times (M/M_J)^{-1} (T/7)^{3/2}\).

Taking the smaller of these estimates, and noting that at 8.6 GHz in the ISM \(\alpha \sim 1\), we can calculate the radio luminosity to compare to the optically thin dust luminosity for the same mass. I find the predicted 850μm to 8.6 GHz ratio to be:
\[
\frac{L_{850}}{L_{8.6}} = 38,156 \times \left(\frac{\mu}{100}\right)^{-1} \left(\frac{T - 2}{5}\right)^2 \left(\frac{T}{7}\right)^{-1}
\]

Note that this result is independent of mass. The prediction fails the goal by a factor of 40. Using the optically thick limit for the submm emission for small clouds improves agreement by a factor of a few. If we had used the second field estimate \((B \propto \sqrt{n})\), we would have overshot in the other direction by a factor of 4. On the other hand, even the equipartition field may be too optimistic. In other words, the uncertainties are even larger than elsewhere in this paper. Even so, there is no a priori reason why we might not have been ten orders of magnitude out, so getting anywhere close is intriguing. Further work may either improve or help to reject the model.

5.7 Summary assessment of hypothesis

Table 3 is a simplified summary of the various key parameters and constraints I have derived for cloud masses ranging from \(0.1 M_J\) to \(10^4 M_J\), assuming a temperature \(T = 7 K\), a flux of 2mJy, a dust-to-gas ratio \(\mu = 100\), and a sky density of \(N = 1000 \text{ deg}^{-2}\). Over this mass range the cloud size ranges from 1 AU to 5 pc, based on an assumption of virial equilibrium maintained by cosmic ray heating, and the distances of such objects range from 15 pc to 10 kpc. There are three factors however that constrain the allowable masses:

(i) The implied local mass density rules out very small clouds, \(M < 0.3 M_J\), if they are not to exceed the robust limit on local unseen matter. (ii) The absence of very obvious extinction holes at high galactic latitude rules out very large clouds, \(M > 100 M_J\).

(iii) If the FIR-mm background is not to be exceeded, the clouds cannot extend more than roughly three times further than the distance deduced for 2 mJy sources. This mildly rules out clouds in the \(M \sim 5 - 500 M_J\) range, but is consistent with small clouds, \(M \sim M_J\), being a disk population.

All the above is for the fiducial values of the secondary parameters. Given the uncertainties, however, we might perhaps conclude that the allowable mass range is \(M \sim 0.1 - 10 M_J\). The cold dark cloud hypothesis has not been so easy to dismiss as brown dwarfs and comets. The various constraints have eventually come close to ruling out the hypothesis, but an interesting mass range remains allowed. Improved observations should be able to fairly conclusively either dismiss or confirm the idea, as discussed further in section 9.

6 Other work on cold dark clouds.

So far I have tried to examine the local hypothesis for SCUBA sources strictly from the viewpoint of the submm data. However over the last few years there has been increasing observation and speculation concerning cold dark clouds.

6.1 Small-scale structure in the ISM

ISM structure on very small scales has been seen in several ways (see review by Heiles 1997). The nature of each of these structures differs significantly from the clouds we have
postulated here, but there may be a way to relate them. AU-scale structure in HI absorption has been shown both directly by VLBI imaging of bright background quasars (Dieter, Welch and Romney 1976; Davis, Diamond and Goss 1996) and by the time variations of the HI absorption spectra seen towards high-velocity pulsars (Frael et al. 1994). The HI column concerned is of the order $N_{HI} \sim 10^{24}$ m$^{-2}$, and so the total estimated mass is of the order $10^{-8} M_\odot$, orders of magnitude smaller than the clouds we have been discussing. Another line of evidence for AU-scale structure is the Fiedler clumps or “extreme scattering events” (ESEs) in quasar radio light curves (Fiedler et al. 1987; Romani, Blandford and Cordes 1987; Fiedler et al. 1994). These are occasional erratic excursions in radio flux which last a few months, and are thought to be due to spatial variations in refractive index in intervening material. Standard modelling of these events require ionised gas at a temperature around 10,000K, obviously rather different from our dense cold clouds. (But see section 6.3). A key feature of both the HI and Fiedler structures is their large covering factor. At low Galactic latitudes at least, the HI variations in pulsars seem to occur in essentially all cases. At high latitudes, the frequency of ESEs indicates a covering factor somewhere in the range $10^{-3} - 10^{-5}$ (Fiedler et al. 1994; Walker and Wardle 1998). The next piece of observational support is the existence of small extremely optically thick structures in the Milky Way. Optically dark patches are well known of course, but the new feature is compact features opaque in the mid-IR, seen both with ISO (Perault et al. 1996) and with the MSX experiment (Egan et al. 1998; Carey et al. 1998). They are very cold, not being seen in IRAS 100\m emitting. However they are not the same as the clouds discussed in this paper. They are resolved, with $\sim 30''$ angular scale, 1-5 pc physical scale, at distance 2-5 kpc, and with mass $10^5 M_\odot$. Their sky density in the Galactic plane is around $N = 20$ deg$^{-2}$, and they are probably not seen at high latitudes, as they are not seen towards the LMC in the MSX data (S.Price, private communication).

### 6.2 Very cold dust emission in the Galaxy and elsewhere

Reach et al. (1995) analysed the COBE-FIRAS spectra over the whole sky and found that they were well fitted by the sum of two greybodies - a “warm” component with $T = 16 - 21 K$ and a “very cold” component with $T = 4 - 7$. The very cold emission is present at high latitudes as well as in the plane. Reach et al argue against very cold dust clouds, suggesting instead emission from very small grains out of equilibrium with the ISM. Sciana (2000) argues for an origin in molecular line emission. When deriving the isotropic extragalactic background, Puget et al. (1996) and Fixsen et al. (1998) attempt to remove the Galactic contribution of course, but the various methods employed all assume either that the angular distribution follows some other well known component, or that the spectral shape of the Galactic dust emission is the same at all latitudes. Reach et al. actually show convincingly that the latter is not the case, so it may not not be too surprising if some of the ubiquitous very cold component is left inside the derived isotropic background. Krugel et al. (1999) have argued that a cold dust component ($T = 10 K$) is also present in the SEDs of several external galaxies, by comparing ISOPHOT far-IR and ground-based mm measurements. The amount of power in the cold component seen by Krugel et al is however much much larger than seen by Reach et al in the Galactic neighbourhood. For the external galaxies, the cold component dominates longwards of about 200\m, whereas in the Reach et al fits (and in the spectral decomposition of the isotropic background I have shown here), the cross-over point is around 1mm. Possibly the contribution of dense cold clouds is modest in the solar neighbourhood, but dominates the outer disks of galaxies, as argued by Pfenniger and Combes (1994). As well as being detectable in emission, it is conceivable that such cold dark clouds make galactic disks opaque. At the solar radius, the covering factor of our clouds will be small (see section 5.5) but possibly it becomes significant in the outer disks. In addition if the clouds are actually part of a fractal ISM, as argued by Pfenniger...
and Combes (1994), then the overall opacity could be much larger.

6.3 Theoretical precedents

Some authors have previously suggested that halo dark matter could reside in the form of cold dark clouds and so be undetected. Pfenniger and Combes (1994) and Pfenniger, Combes and Martinet (1994) argued that such clouds would be at or near the traditional hierarchical fragmentation limit (a few Jupiter masses), and further argued that flat rotation curves could be explained with massive outer disks dominated by such molecular clumps. Gerhard and Silk (1996) argued for $1M_\odot$ clumps spread through the halo, suggesting that otherwise too much $\gamma$-ray background would be produced. Very recently however, Kalberla et al (1999) have successfully modelled the EGRET high-latitude emission with a halo containing Jupiter mass clumps of size $6$ AU, totalling $10^{11}M_\odot$. De Paolis et al (1995) and Draine (1998) have argued that halo micro-lensing events could be due to molecular clouds. Walker and Wardle (1998) arrived at similar characteristics by modelling the ESEs. One problem with these events is that the ionised gas deduced is at a pressure orders of magnitude higher than the interstellar medium. The orthodox solution is to assume that the structures concerned are transient, such as knots in supernova remnants. Walker and Wardle instead suggested that the ESEs arise in an ionised wind from a more massive object. The several-AU size scale is set by the timescale of ESEs plus an assumed halo velocity of $500$ km$^{-1}$, and the mass of around $1M_J$ deduced by assuming virial equilibrium at a temperature of a few K. The covering factor of ESEs then leads to a large total mass in such clumps, consistent with the dark halo. Most recently Sciama (2000) has calculated the cosmic ray heating and FIR emission of such clouds, on the assumption that they are dustless (and so arriving at a much lower predicted luminosity than discussed in this paper).

7 Have we seen the dark matter?

The mass range to which our putative clouds are constrained implies a local mass density which, while not being dynamically dominant locally, is about that expected for the local dark halo contribution. However, I have argued that such clouds cannot extend further than a few hundred pc without violating the background. Furthermore, if they were to extend through the halo, they would produce a much larger covering factor of extinction features. Walker and Wardle (1998) were well aware that extinction effects are the main argument against their hypothesis, and suggested that either the ESE clouds are dust free, or possibly that they are so cold that the dust grains have settled into a rocky core. However the objects postulated in this paper cannot be dust-free or we wouldn’t see them. It is tempting to speculate that there are two populations of dense cold clouds. Population-I is a disk population, containing dust, heated by cosmic rays, and produces the SCUBA sources. Population-II is a halo population, and is either primaeval with no dust, or with a rocky core, and produces the ESEs.

Micro-lensing studies show evidence for dark bodies at around a few tenths of a solar mass, and seem to strongly rule out objects in the mass range we are considering here (Alcock et al 1996). However, this only applies to compact objects. For Jupiter mass objects lensing much more distant objects, the Einstein radius is about $0.03$ AU for a lens at $100$ pc, and still only $0.3$AU for a lens at $10kpc$. As this is much smaller than the object size, no significant amplification will occur for cold dark clouds within our own halo. However, the same objects in the halos of external galaxies will appear compact and could lens background quasars (Walker 1999). Finally, it has been suggested that gas lensing by small clouds can produce
the kind of stellar amplification events seen in large stellar monitoring programmes (Draine 1998), and that conceivably objects with Walker-Wardle like parameters (i.e. Jupiter mass and a few AU in size) can produce the entire event rate.

8 Cold Dark Clouds as failed stars.

Regardless of their contribution to the dark matter problem, cold dark clouds are very interesting new objects, and it will be important to confirm whether they exist. The mass range concerned, around a Jupiter mass, is close to the traditional fragmentation limit for collapsing clouds set by internal opacity (Hoyle 1953; Lynden-Bell 1973; Rees 1976). Modern hydrodynamic simulations of star formation seem to show that the fragmentation limit is set by the turbulence scale, and is rather larger, but depends on physical conditions (e.g. Padoan and Nordlund 1999). The objects we are discussing are not as compact as stars or brown dwarfs, but far more compact than molecular clouds. Viewed this way in the context of star formation they seem to be alternative end-points for collapsing clouds. But is it reasonable that such objects could exist? Here I look briefly at three problems. (i) Is there a heating source? (ii) Are they stable? (iii) Will they survive disruption?

Once a protostellar cloud becomes opaque to heating by external starlight, it can collapse, and as it radiates heat away it collapses further and gets hotter. This process continues until a new source of support emerges. For massive enough clouds, this is of course nuclear fusion in the centre producing a source of heat and pressure. For a small cloud, we have seen in section 5.3 that the cooling time is very short, so unless there is an external heating source, it will continue to collapse until becoming degenerate - i.e. a brown dwarf. The heating source that could prevent this is cosmic rays, as they will reach deep into even these very thick clouds. The local CR energy density is quite significant, $\epsilon_{\text{CR}} \sim 1.80 \text{ eV cm}^{-3}$ (Webber 1998), but it is not clear what fraction of this is available for heat. Sciama (2000) has considered the CR heating of Walker-Wardle-like clouds, but assumed that cooling was by molecular line emission. Here I assume cooling by dust emission. Integrating over a greybody spectrum with $\beta = 1.3$, assuming the parameters of a one Jupiter mass cloud as derived in this paper, and assuming that 1% of the CR energy density is available for heat, I arrive at an equilibrium temperature of $T = 9.5$, very much in the range we are looking for. This depends very weakly on most of the parameters concerned, including the efficiency of heating (roughly to the power 0.1)

But will a CR heated equilibrium be stable? The sound crossing time is very short (~100 years) so the objects are stable against pressure perturbations and should find a hydrostatic equilibrium equivalent to the virial equilibrium we have been assuming. However this equilibrium may be unstable on the cooling timescale ($10^4$ years). If the object collapses, it will heat up and radiate faster than the cosmic rays can re-supply the energy, leading to further collapse. This lack of thermal stability is certainly the major theoretical objection to the cold dark cloud picture. Wardle and Walker (1999) discuss ways to circumvent this problem by the sublimation of solid hydrogen. The possibility of magnetic or rotational support should also be investigated. Finally, it is possible our clouds are not long lived objects, but part of a dynamic interstellar medium in which clouds are repeatedly destroyed and re-formed (Pfenniger and Combes 1994).

Will the clouds be disrupted by passing stars? The tidal disruption radius for a star of mass $M_*$ will be given by
\[
D_{\text{disrupt}} = 316 \text{AU} \times \left( \frac{M_c}{M_\odot} \right)^{1/2} \left( \frac{T}{7} \right)^{-1} \left( \frac{M_*}{M_J} \right)^{1/2} \left( \frac{M_\odot}{0.5M_\odot} \right)^{-1} \left( \frac{T_7}{7} \right)^{-1}
\]

Taking a mean stellar mass of \(0.5 M_\odot\), a density of \(n = 0.1 \text{ pc}^{-3}\), and a typical random velocity of \(v = 30 \text{ km s}^{-1}\), the two-body collision timescale gives

\[
\tau_{\text{disrupt}} = 8.4 \times 10^{10} \text{ years} \times \left( \frac{M_c}{M_J} \right)^{-1} \left( \frac{M_*}{0.5 M_\odot} \right)^{-1} \left( \frac{T}{7} \right)^2
\]

The conclusion is that only low mass objects are long lived. Objects more massive than \(100M_J\) have lifetimes less than the age of the Galactic disk. Re-assuringly, the massive objects which we earlier concluded cannot dominate the SCUBA counts without violating observational constraints, are also those which we do not expect to survive in large numbers. We can likewise calculate a cloud-cloud collision timescale, which gives a similar timescale, \(\tau = 9.7 \times 10^{10} \text{ years} \times (M/M_J)^{-1/2}\). Gerhard and Silk (1996) calculate that a cloud can only survive such a collision if \(N_H > 10^{29} \text{ m}^{-2}\), again suggesting that only low mass clouds can survive. Finally we may ask how often a typical star (like the Sun) should wander through a completely opaque cloud - is this what killed the dinosaurs?? Given the cloud size and population density for our clouds derived in earlier sections, I find that such encounters are very rare, \(\tau = 3.9 \times 10^{11} \text{ years} \times (M/M_J)^{-1/2}\), although the probability of such an encounter may be significantly enhanced when the sun crosses a spiral arm (see Leitch and Vasisht 1997).

However stars actually form, stars are stable against disruption and stellar mass cold clouds are not. Planetary mass cold clouds are stable against disruption, but it remains to be seen whether they are thermally stable. The contentious issue then is whether nature forms cold dark clouds or brown dwarfs, and how it chooses.

9 Testing the hypothesis

Several lines of investigation look promising.

(i) Looking for unresolved or marginally resolved dark spots against diffuse background light sources. So far we have restricted the allowed mass range on the basis that no such gross effects are known, but a more careful search against carefully chosen sources is obviously feasible. Furthermore any such dark spots should coincide with bright spots in submm maps.

(ii) Looking for stellar switch-on-offs. Given the deduced covering factor, about one background star in every million should be occulted at any one time. With a size of \(\sim 10 \text{ AU}\) and a random disk velocity with respect to the sun of say \(30 \text{ km s}^{-1}\), the occultation would last a year or two. Such rare but dramatic appearances and disappearances may just be detectable with existing datasets such as those of the MACHO or OGLE projects.

(iii) Over a period of years the submm sources should show measurable proper motion. This won’t be detectable with SCUBA, but should be with IRAM. If the cold dark clouds are also radio sources, then the VLA sources should also show proper motion, and given the accuracy of radio positions this may be an easier project.
(iv) Zero redshift molecular emission lines may be measurable. At a temperature of $T = 4 - 9K$ $H_2$ will not be excited, but the lowest states of CO are at $2 - 3K$, so should be excited. I have not attempted to calculate the expected line fluxes, given the uncertainty in conditions and optical depth. Downes et al (1999) made a sensitive line search in HDF 850.1 but only in narrow windows where redshifted lines would be expected.

(v) As suggested by Walker and Wardle (1999), clouds relatively near stars may show up as H$\alpha$ sources from the ionised winds. The scattered starlight might also be detectable.

(vi) Somewhere on the sky a dark object with a submm flux of many Jy and and a size of $30''$ may be lurking, somewhere on the edge of the Oort Cloud. Possibly such an object has already been detected by its effect on cometary orbits (Murray 1999).

(vii) Source counts should show a moderate dependence on Galactic latitude, depending on the scale height of the population.

(viii) The fraction of clearly identified sources should depend on wavelength. At 450 $\mu$m most sources would be identified with galaxies at redshift $\sim 1 - 3$. At 1.3 mm most sources would be blank.

(ix) At bright counts (brighter than about 10 mJy) source counts should be Euclidean.

10 Conclusions

The lack of clear optical identifications for a large fraction of faint submm sources is pushing us towards believing that they are very high redshift objects, but we must first scrupulously consider alternative possibilities. In local hypotheses, these sources are extremely cold, $T \sim 7$ K. They cannot be brown dwarfs or solar system bodies without grossly violating simple constraints. Cold dusty clouds are harder to rule out completely, but if such objects are not to violate limits on local mass density, extinction features, and the FIR background, they are constrained to have masses similar to Jupiter to within an order of magnitude, and to be a Galactic Plane population. Such clouds do not explain the dark matter problem, unless there is a much larger population of similar but dust-free objects. (In this respect my proposal differs from most of the rest of the literature in this area which involves a pervasive but dust-free halo population). If such cold dusty clouds do exist, they are an important new component of the interstellar medium, and may be an important part of the star formation puzzle. The main theoretical objection is that such objects should be unstable to collapse on a thermal timescale, but they may be short-lived objects which are part of a dynamic ISM, as argued by Pfenniger and Combes (1994).

The majority of faint SCUBA sources clearly really are distant galaxies. However if even a quarter or a third of the SCUBA sources are actually local objects, the cosmological implications are significant, as this would selectively remove the objects believed to be at $z > 3$.

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**TABLE 1 : MEASURED FLUXES OF HDF 850.1**

| Wavelength | Flux       | Reference |
|------------|------------|-----------|
| 15µm       | <23µJy(3σ) | (1)       |
| 450µm      | <21 mJy (3σ) | (1) |
| 850µm      | 7.0±0.4 mJy | (1)       |
| 1350µm     | 2.1±0.5 mJy | (1)       |
| 1270µm     | 2.2±0.3 mJy | (2)       |
| 2.8mm      | <0.5 mJy (3σ) | (2) |
| 3.4mm      | < 0.4 mJy (3σ) | (2) |
| 3.5cm      | 7.5±2.2µJy  | (3,2)     |
| 20cm       | <23µJy(3σ)  | (4,2)     |

Table 1: Measured Fluxes of HDF 850.1 at various wavelengths, compiled from the literature. References: (1) Hughes et al 1998 (2) Downes et al (1999) (3) Richards et al (1998) (4) Richards (1999)

**TABLE 2 : TEMPERATURE LIMITS FROM HDF 850.1 FLUX RATIOS**

| ratio                  | $\beta = 0$ | $\beta = 1$ | $\beta = 1.5$ | $\beta = 2$ |
|------------------------|-------------|-------------|---------------|-------------|
| $S(450\mu m)/S(850\mu m)$ | < 2.1       | T<9.4       | T<7.6         | T<6.4       |
| $S(850\mu m)/S(1300\mu m)$ | 3.2±0.5    | T<70        | T>8.3         | T=6.0-49.6  |
| $S(1300\mu m/2800\mu m)$   | < 5.7       | excluded    | T>6.5         | T>4.1       |
| combined               | excluded    | T=8.3-9.4   | T=6.0-7.6     | T=4.7-6.4   |

Table 2: Limits on single temperature models for HDF 850.1, based on individual flux ratios, assuming greybodies with various values of the emissivity index $\beta$. The limits and ranges used are approximately 95% confidence. Note that the SCUBA 1350µm and IRAM 1270µm fluxes have been averaged and taken as a 1300µm flux.

**TABLE 3 : SUMMARY OF CONSTRAINTS**

|                         | 0.1 M$_J$ | M$_J$ | 10M$_J$ | 100M$_J$ | 10M$_\odot$ |
|-------------------------|-----------|-------|---------|----------|-------------|
| optically thick or thin ? | thick     | intermediate | thin | thin | thin |
| Virial Radius           | 1 AU      | 10 AU | 100 AU  | 1000 AU  | 5pc         |
| Extinction through cloud (A$_V$) | A$_V$=10$^5$ A$_V$=10$^4$ A$_V$=1300 A$_V$=130 A$_V$=1.3 |
| Population mass density (M$_\odot$ pc$^{-3}$) | (0.3) | 0.01 | 0.003 | 0.001 | 10$^{-4}$ |
| Approx. distance limit  | 45pc      | 300pc | (1 kpc) | (3 kpc) | 30 kpc      |
| Angular radius          | 0.07$''$ | 0.1$''$ | 0.3$''$ | (1$''$) | (10$''$) |
| Covering factor         | 10$^{-6}$ | 10$^{-6}$ | 10$^{-5}$ | (10$^{-4}$) | (10$^{-2}$) |

Table 3: Summary of deduced cloud properties as a function of assumed cloud mass. The figures shown are rounded values, and assume (where appropriate) dust temperature T= 7K, dust-to-gas ratio $\mu = 100$, surface number counts N=1000 deg$^{-2}$, and submm flux S(850µm= 2 mJy). The distance limit is very approximate and comes from the requirement not to exceed half the submm background flux. Boxes taken to be excluded by observations are bracketed.
Figure 1: Decomposition of the FIR-mm background spectrum. The actual data are not shown here. The circles represent the parameterisation found by Fixsen et al. to fit the data. The thin lines are both single temperature greybody spectrum. Each has $\beta = 1.3$. The upper line has $T = 17$ and the lower line has $T = 7$. The thick line is the sum of the two greybody spectra.