Observing Baryonic Dark Matter with ALMA

Hideyuki Kamaya\textsuperscript{1,2} and Joseph Silk\textsuperscript{1}

\textsuperscript{1} Astrophysics, Department of Physics, Denys Wilkinson Building, University of Oxford, Oxford OX1 3RH
\textsuperscript{2} Department of Astronomy, School of Science, Kyoto University, Kyoto, 606-8502, Japan

ABSTRACT

It has recently been argued that the unidentified SCUBA objects (USOs) are a thick disk population of free-floating dense, compact galactic gas clumps at a temperature of about 7 K. The characteristic mass scale is constrained to be on the order of a Jupiter mass, and the size is about 10 AU. A typical galactic USO is located at a distance from the sun of about 300 pc. We have calculated the molecular emission lines from these low temperature clouds. We consider three molecules: HD, LiH, and CO. HD is optically thin in the cloud, LiH is a molecule with a large electric dipole moment, and CO is an abundant molecule that is observed in dusty clouds. Our estimate for the typical object shows that LiH may be detectable by the future sub-mm array project, ALMA; its expected flux is at the mJy level and the line width is about $10^5$ Hz. Although typical galactic USOs are chemically and dynamically transient, the younger USOs will be recognisable via LiH emission if about a hundred USOs are observed. If USOs are confirmed to be of galactic origin, the total baryonic budget will need to be reevaluated.

Key words: ISM: clouds — galaxies: ISM — submillimeter — cosmology

1 INTRODUCTION

Standard cosmic nucleosynthesis calculations together with the current observational measurements of the abundance of $^2$D, in addition to limits on $^3$He, $^4$He, and $^7$Li, constrain the cosmic baryon density to be (O'Meara et al. 2001)

$$\Omega_b h^2 = 0.02 \pm 0.002.$$  \hfill (1)

The Hubble constant, $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$, is estimated to be $h = 0.72 \pm 0.08$ (Freedman et al. 2001). Hence the cosmic baryon density is between 0.03 and 0.05. There is a similar constraint on $\Omega_b h^2$ from the CMB (e.g. Ferreira 2001; Bartlett 2001 for reviews), the most recent result being $\Omega_b h^2 = 0.033 \pm 0.013$ (Stompor et al. 2001). Stringent constraints from the CMB anisotropies limit the extreme possibility that baryons account for all of the matter in the universe (Griffiths, Melchiorri, & Silk 2001).

In fact, the baryon budget is poorly known (cf. Persic & Salucci 1992; Gnedin & Ostriker 1992; Bristow & Phillipps 1994; Fukugita, Hogan & Peebles 1998). Table 3 of Fukugita et al. summarises the results. While the stellar contributions are minor, hot plasma in clusters and groups of galaxies is the dominant contributor to the observed baryon budget. However, for example, the contribution from the intracluster medium is considered to be only in the form of hot plasma.

Any warm gas or small, cold clouds in the clusters would contribute to the baryon budget. While the conclusion of Fukugita et al. is consistent with $\Omega_b$ as constrained above, the possibility remains that the contribution of small cold clouds is significant. This has indeed been argued to be the case for the intracluster medium, but a stronger case can perhaps be made for the presence of such clouds in less hot environments, such as the intra-group medium and galaxy halos, where observations are less constraining. For example, if there is undetected galactic HI and CO, the galactic baryon budget in the form of tiny very cold clouds may be underestimated.

Possible dynamical structures of such tiny very cold clouds have been examined by Gerhard & Silk (1996). According to these authors, in order to stabilize these low temperature clouds against collapse, two mechanisms are of interest. One is gas-dust collisional heating, and the other is the effect of the gravitational potential wells of collisionless dark matter. Other aspects are discussed in many papers (e.g. de Paolis et al. 1995a, 1995b; Henriksen & Widrow 1995, Draine 1998; Kalberla et al. 1999; Wardle & Walker 1999). In this Letter, we also comment on the dynamical properties very briefly in the next section, focussing on the observational claim that some very low temperature clouds may have retained or acquired dust (e.g. Lawrence 2001).

Indeed, it has been suggested observationally that halo dark matter could reside in the form of cold dark clouds and
so be undetected. Pfenniger & Combes (1994) and Pfenniger et al. (1994) argued that such clouds would be at or near the traditional hierarchical fragmentation limit and further argued that flat rotation curves could be explained by baryonic dark matter in this form. Walker & Wardle (1998) examined observational constraints in the radio bands for the clouds. The observational possibility of an emission line forest (i.e. quasi-continuum) from the clouds was first examined by Sciama (2000). An extensive review of the small-scale interstellar medium, which may be related to these tiny cold clouds, is presented in Heiles (1997). In the same context, Lawrence (2001) has proposed a possible galactic origin for the unidentified SCUBA objects (USOs). In order for the USOs to be galactic, the far IR/mm background and SCUBA source counts at 400 and 800 \( \mu m \), together with dynamical limits on galactic dark matter, constrain the cloud parameters, if distributed throughout the galaxy, to have low temperatures \( \sim 7K \), Jupiter-like masses \( M_J \), and to be very small, about 10 AU in size. As long as these characteristics are imposed because of the dynamical limits, it may be that USOs contribute to the baryon budget in the intracluster and intra-group medium although they have a small covering factor over the sky. In this Letter, we propose a simple observational strategy for the direct detection of galactic USOs.

2 PHYSICAL CONDITION OF UNIDENTIFIED SCUBA OBJECTS

The physical conditions in USOs may be summarised as follows. Lawrence (2001) posed a number of constraints on the sub-mm sources. According to his discussion: (i) the objects must have an SED consistent with what is known from the brighter sub-mm sources; (ii) their distribution on the sky must be at least roughly 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. From these constraints, Lawrence developed a possible model for galactic SCUBA point-sources, summarised in Table 1 of his paper. We have extracted three representative models in our Table 1. Jupiter–mass objects satisfy all of the above criteria. Radio and sub-mm fluxes and upper limits constrain the galactic USOs to have a temperature of about 7 K. We note that the SCUBA sources show continuous emission in the sub-mm band, and hence they must retain some dust. In a related paper, it is shown that the USO covering factor is quantitatively constrained by occultation limits, using data from microlensing experiments (Kerins, Binney and Silk 2002).

Possible dynamical properties of USOs are also of interest. Here, we review very briefly the suggestions of Gerhard & Silk (1996). The expected low temperature clouds in the galactic halo, if primordial, could also be maintained in the gravitational potential wells of mini-clusters of collisionless dark matter. Following Umemura & Ikeuchi (1986), Gerhard & Silk found that the tendency to self-gravitational fragmentation of the very low temperature clouds is possibly stabilised by the gravity of the minicluster of collisionless dark matter. The maximum mass fraction of the cold gas relative to collisionless dark matter is expected to be about 0.01 – 0.1. Thus, the total mass of a typical USO as discussed by Lawrence could be as large as 0.01 – 1.0 solar mass without breaking the universal collisionless cold dark matter assumption. Unfortunately, however, the current model requires USOs to have dust, so that USOs are unlikely to be primordial. Of course they may have accreted substantial amounts of dust in traversing the galactic disk (Kerins et al. 2002). Another means of avoiding gravitational contraction and star or planet formation is possible if the heating of the gas is dominated by gas-dust collisions and the dust temperature is much higher than that of the gas (Gerhard & Silk 1996). This effect can stabilize the clouds for the age of the Galaxy, since the effective specific heat ratio becomes larger than 4/3. To check this possibility, the dynamical coupling between dust and cold gas is examined in a later section.

3 MOLECULE SELECTION

We examine the possibility of observing line emission from galactic USOs. The USOs are very low temperature clouds, and so some molecular emission is expected in the radio and sub-mm bands. The USOs consist primarily of hydrogen molecules. Unfortunately, since the first level for rotational excitations of \( H_2 \) is at 515 K, the expected line flux of \( H_2 \) is not large. Hence, Sciama (2000) argues that there is a quasi-continuum of many lines of hydrogen and heavy molecules (\( H_2 \), CO, \( H_2O \), HCl, O\(_2\)) to obtain the cooling rate of gas in the clouds proposed by Walker and Wardle (1998). In this Letter, we further consider three typical emission lines for the following reasons.

The first molecule we examine is HD. This molecule is selected since it should exist when the expected small cold cloud is composed mainly of \( H_2 \). The HD molecule is generally optically thin in the clouds since HD has a small electric dipole moment. This moment has been measured in the ground vibrational state from the intensity of the pure rotational spectrum by Trefler & Gush (1968). The measured value is about \( 5.85 \times 10^{-4} \) Debye (1 Debye = \( 10^{-18} \) in cgs units). Since the first rotational level is about 128 K, the corresponding wavelength is 112 \( \mu m \). In this paper, we set the D abundance to be \( 4 \times 10^{-5} \) in number and assume that all the D is in the form of HD. The fraction of rotationally excited HD is determined for a thermal distribution.

The second molecule we consider is \( \text{LiH} \), which has a large electric dipole moment of 5.9 Debye. Hence the detection of \( \text{LiH} \) is generally of interest for interstellar astrophysics. Indeed, there is a real possibility that \( \text{LiH} \) is an important emission source (Lepp & Shull 1984) because of its large electric dipole moment. Furthermore, the detection of \( \text{LiH} \) itself is interesting because the surface conditions of the (pre-Galactic) USOs must be linked with the pre-Galactic cosmic-ray particle flux. This is because Li has the unique property of being produced not only by big bang nucleosynthesis, but also by spallation of Galactic cosmic-ray particles on interstellar matter nuclei (of course, stellar nucleosynthesis is also important). Its abundance is expected to be very small (e.g. \( \sim 10^{-10} \) in number; we assume this value for a typical case), although the variance of the measured abun-
dance of Li is known to be large (e.g. Hill, Barbuy, & Spite 1997, Vangioni-Flam, Coc, & Cassé 2000, Travaglio et al. 2001). The first rotational level of LiH is only at about 21 K and its rest wavelength is about 0.67 mm. For the case of LiH, we also adopt a thermal distribution.

The third molecule we consider is CO. This is the most common heavy molecule in mm astronomy of the interstellar medium, which is why we select it. Comparison of the abundance of CO to that of LiH may provide useful information on the evolution and formation of USOs. The USOs have acquired dust, and so would also presumably have the C and O to form CO in situ. The CO dipole moment is 0.112 Debye, and the first rotational level is about 5.5 K, corresponding to 2.6 mm in the rest frame. We assume the CO/H ratio to be 1.0 × 10^{-4} which is about that of the solar neighbourhood and consistent with the model proposed in Lawrence (2001). To determine the abundance in the J = 1 level of CO, we adopt a thermal distribution. We note that the level population of CO up to J = 3 can be thermally excited even at a temperature of 7 K.

4 RESULTS

To obtain the luminosity in the emission lines, we need to specify the cloud volume, optical depth, and critical density for collisional de-excitations to be dominant. Fortunately, a galactic USO is very dense by definition (see table 1). For all of the ground rotational emission lines of the three molecules, the gas density of 0.1M_J and 1.0M_J clouds is much larger than the critical density. The density of the 10 M_J example is comparable to the critical density of the ground rotational emission of LiH, while it is much larger than the critical density for HD and CO. In these situations, to estimate the luminosity of the emission lines, we need the de-excitation probability, A_{J′J}, and the optical depth, τ_{ν,J′J}. We adopt a useful analytical formula for these quantities:

$$A_{J′J} = \frac{64\pi^3\mu^3}{3hc^3}\frac{J^3}{2J+1}$$ (2)

and

$$\tau_{ν,J′J} = \frac{A_{J′J}\nu_j^2}{8\pi\nu_j^3}\left(\frac{g_{J′}}{g_J} - \frac{n_{J′}}{n_J}\right)\frac{R_J}{\deltaν}.$$ (3)

where ν_j is the frequency of the J′ → J transition, h the Planck constant, c the light speed, D the electric dipole moment, J the rotational quantum number, R_J the cloud radius, δν the velocity dispersion, and g_j the statistical weight of 2J + 1. The velocity dispersion corresponds to Doppler broadening, and is taken to be equivalent to the sound speed at 7K. The effect of the turbulence and rotation of an USO can contribute to δν. USOs are assumed to be virial equilibrium, and then the effect of the turbulence and the rotation should be the same order as that of the thermal motions. Hence, the uncertainty of δν owing to cloud turbulence and rotation is a factor of a few.

The clouds are very cold, and so we consider mainly the first rotational level of each molecule as a typical case. With (3), the escape probability, ε_{ν,J′J}, of the photons becomes

$$ε_{ν,J′J} = \frac{1 - \exp(\tau_{ν,J′J})}{τ_{ν,J′J}}.$$ (4)

Finally, we can estimate the emission line as $n_{i,J′}E_{J′J}\Delta J′\epsilon_{ν,J′J}$ erg cm^{-3} sec^{-1}, where $n_{i,J′}$ is the number density of the i-molecule with rotational level J′ and E_{J′J} is the transition energy between J′ and J. This formula is reasonable as long as the net gas density is above any relevant critical density and the temperature is very low. For simplicity, we assume that the cloud is uniform.

The expected fluxes at the Earth are summarised in table 1 for each model of the very low temperature cloud of Lawrence (i.e. for a typical galactic USO). Our results are the following.

1) HD: the three flux levels are similar to each other. This is because HD is optically thin and the cloud model of Lawrence is well constrained by the other observational flux limits. That is, the size of the cloud and the typical distance from us is specified. These results for HD confirm that our estimates are reasonable. Since the flux level of HD is so low, it will be very difficult to detect HD from the galactic USOs directly.

2) LiH: we find this molecule to be very important. The flux level is at the mJy level, which should be observable by ALMA. ALMA is a ground-based radio interferometric facility, and will consist of 96 12-m antennas. A detailed recent review is found in Takeuchi et al. (2001), from which we infer that the 5 frequencies at 350 μm, 450, 650, 850, 1.3 mm, 3.0 mm are expected to be 390, 220, 120, 16, 7.5, 4.6 μJy, respectively (8-GHz bandwidth). Obviously, the predicted frequency of LiH is located in the range of ALMA. The typical line width is about 10^5 Hz. The frequency resolution limit of ALMA is about 4 × 10^4 Hz. Direct detection of LiH from galactic USOs should be possible by ALMA.

3) CO: the expected flux level seems to be marginal for current observational facilities, while the width of the line is very narrow because of the low temperature. Then, it is very reasonable to infer that these very cold clouds would not yet been observed. However follow-up CO detection is important if LiH is detected. This is because we can confirm temperature and density of the USOs.

To predict the expected signal-to-noise ratio, it is necessary to know the continuum level of the flux. We estimate this under the assumption that the dust emits optically thick blackbody radiation. For the typical case, the dust number density, n_{dust}, is 18.5 cm^{-3} and the mean surface area is about 1.5 × 10^{-13} cm^2, both of which are determined under the assumption of a standard MRN number distribution function (Mathis, Rumpl, & Nordsieck 1977) with the constraint that the total dust mass is 0.01 × total mass of the cold cloud, taken to be M_J for a standard galactic USO. The specific density of dust is assumed to be 2.0 g cm^{-3}, and the range of dust radii, a, is adopted to be 0.0001 – 3.0 × 10^{-7} cm. Since the size of the cloud is 1 – 100 AU, then we estimate the dust continuum to be from an optically thick dust sphere with a typical radius corresponding to each dust model. Each estimated flux is presented in table 1 for each of the wavelengths of HD, LiH, and CO. A schematic view is also presented in figure 1 with expected line emission for the typical case of M_J.

\[1\] http://www.alma.nrao.edu
5 DISCUSSION

In the previous sections, USOs are assumed to have a constant abundance of molecules. However, USOs are cold and dense. In such objects, molecules stick to dust and are depleted from the gas phase. Then, we must examine the depletion of LiH and CO. This is necessary if we try to find observational feasibility. Unfortunately, the depletion of LiH is not well understood, and so we start by considering the case of CO.

According to Duley & Smith (1995), the sticking probability, $S_{\text{CO}}$, of CO on dust is about $0.037 - 0.037$. They derived this from observations of heavy reddened regions in the Taurus molecular clouds. For order of magnitude estimates, we shall adopt 0.01 as $S_{\text{CO}}$. The exponential depletion rate is defined by $S_{\text{CO}}\pi a^2 n_{\text{dust}} v_s$, where $v_s$ is the sound speed of the gas around the dust. For $a$ and $n_{\text{dust}}$, the characteristic values for the MRN distribution are assumed. Then, the depletion rate is $0.3 \times 10^{-7}$ s$^{-1}$ with $v_s = 1.13 \times 10^4$ cm s$^{-1}$ for the case of $M_1$.

This is rather large, but of course we also need to specify the rate at which cosmic rays and ambient photons may eject molecules from the grain surfaces. This is poorly known, but unlikely to be dominant in these very dense clouds. If CO were to be observed from a typical galactic USO, it would most likely be transient, and it would be difficult to confirm the predicted universality of USOs.

The order of magnitude of the sticking probability of LiH, $S_{\text{lih}}$, may not be much smaller than $S_{\text{CO}}$. Then, observation of LiH at the mJy level would require the USO to be young, and might mean a significantly small value of $S_{\text{lih}}$ as long as CO is not detected. How transient is the LiH gas phase abundance likely to be? The dynamical evolution time of a USO is about a free-fall time, which is about $5.75 \times 10^8$ s for our standard case of $M_1$. Even if the USOs are more long-lived than the dynamical time, the gas and dust would circulate at the sound speed on this time-scale, and this circulation should ensure a fresh supply of gas-phase LiH and CO as the dust from the cloud core is exposed to a less protective environment. Thus if we were to observe about 100 USOs, we would expect at least one of them to emit a strong LiH line and a supplementary weak CO line. This is performed simply by observing the brightest USOs.

Since LiH is transient, it is useful to calculate the emission flux with a smaller abundance than that of the typical model with a Jupiter mass. We try to estimate this by postulating abundances of $10^{-12}$ and $10^{-14}$. The expected line fluxes are 4.81 mJy for $10^{-12}$ and 0.35 mJy for $10^{-14}$. At the abundance of $10^{-12}$, the emission line is still optically thick, and the flux hardly decreases relative to that of the typical case. In the case of $10^{-14}$, the line emission is optically thin, and then the flux is reduced. The time-scale for the decrement from $10^{-10}$ to $10^{-14}$ is only several times the depletion timescale. Thus, the detected USOs are expected to be younger than the dynamical time-scale, as long as the spallation of cosmic-ray particles on nuclei at the surface layers of USOs is not efficient. Furthermore, if such very low abundance molecule is observable, $^6$LiH may be detectable near LiH by ALMA as long as the USO is very young. This is because abundance of $^6$Li can be about $10^{-13}$ even if it is primordial. When a USO is old, abundance of $^6$LiH decreases much below $10^{-14}$. We may find $^6$LiH line near LiH, when we observe more USOs than a hundred.

We also comment on the dynamical coupling between gas and dust. We consider the typical case of a cloud mass of $M_1$. The time-scale for dust interaction with the gas is $1/(\pi a^2 n_{\text{dust}} v_s)$, and is equal to $3.3 \times 10^3$ s if a standard MNR distribution of dust is assumed. The dynamical timescale, which can describe the evolution timescale, is about $5.75 \times 10^8$ s, the free-fall timescale. Thus the dust frequently interacts with dust during the dynamical evolution of a galactic USO. Hence, the coupling between dust and cold gas can be well established on the dynamical time-scale. Since the dust-gas coupling is good, this also means that the temperature of dust and gas is nearly the same. That is, the effective specific heat ratio can be smaller than 4/3. Hence, the expected cold cloud should be transient on a dynamical time-scale since it is unstable to gravitational contraction. This is another constraint on a model for USOs. The temperature of the clouds may be eventually confirmed by detection of CO lines if future high resolution of spectroscopy is possible (Sciama 2000).

The preceding discussion does not contradict the universality of the galactic USOs, although the observed USOs should be transient chemically and dynamically. However we need to find a production process for transient USOs. An interesting recent discussion proposes an origin for free-floating compact substellar objects of about Jupiter mass (Boss 2001). According to the paper by Boss, searches for very low mass objects in young star clusters have uncovered evidence for free-floating objects with inferred masses possibly as low as $5-15$ Jupiter masses, similar to the masses of several extrasolar planets. He shows that the process that forms single and multiple protostars, namely, collapse and fragmentation of molecular clouds, might be able to produce self-gravitating objects with initial masses less than $1 M_J$ provided that magnetic field tension effects are important and can be represented approximately by diluting the gravitational field. If such fragments can be ejected from an unstable quadruple protostar system, prior to gaining significantly more mass, protostellar collapse might then be able to explain the formation of free-floating objects with masses below $13 M_J$. We note that ejected material can be in the form of extremely dense and cold clumps, and speculate that this mechanism may be responsible to the origin of a galactic population of USOs. A more precise examination of this possibility is needed.

In any case, if LiH and CO were to be detected from galactic USOs, it would be necessary to consider a production process for USOs. A promising candidate mechanism is the gravito-magnetic scattering of dense clumps from star-forming regions (Boss 2001). In the galactic halo, stars can form, for example, in HI supershells and in infalling, compressed HI high velocity clouds. Hence free-floating USOs may originate in halo star-forming regions, although any contribution to the overall population of such objects is highly uncertain because of our sparse knowledge of halo star-forming regions.
6 CONCLUSIONS

It has been suggested that some halo and disk dark matter could reside in the form of cold dark clouds and so be undetected. In particular, Lawrence (2001) has constrained the physical properties of such halo baryonic dark matter candidate objects by appealing to submm-mm observations. According to our observational predictions for Lawrence's objects, LiH emission lines can in principle be detected by ALMA. This will provide a strong constraint on models for the galactic unidentified SCUBA sources, which we refer to as USOs in this Letter. According to Gerhard & Silk (1996), galactic USOs can be dynamically transient. In the current work, furthermore, since the chemical depletion of CO and presumably LiH is significant, then they are also chemically transient. Hence, we may need to observe around 100 USOs for clear evidence of the galactic USO candidates that we have postulated. If their reality is established, the contribution of USOs as well as MACHOs to the galactic baryon budget will need to be re-examined.

ACKNOWLEDGEMENT

We express our gratitude for the referee, A. Lawrence, whose comments helped clarify the discussions and presentation of the manuscript. H.K. is grateful to Profs. S.Mineshige, S.Inagaki and R.Hirata for their encouragement.

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Figure 1. Schematic spectral of a typical galactic USO of M_J. The continuum is optically thick dust black body. Each of three lines is HD (0.11 mm), LiH (0.67 mm), and CO (2.60 mm), respectively. The vertical axis is ticked in log-scale of mJy, while the horizontal axis in normal wavelength of mm.

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Table 1. Expected Emission Lines

|    | 0.1MJ | 1.0MJ | 10.0MJ |
|----|-------|-------|--------|
| Radius (AU) | 1.0 | 10.0 | 100 |
| Density (cm$^{-3}$) | $4.0 \times 10^{12}$ | $4.0 \times 10^{10}$ | $4.0 \times 10^{8}$ |
| Population mass ($M_{\odot}$ pc$^{-3}$) | 0.3 | 0.01 | 0.001 |
| Distance (pc) | 45 | 300 | 1000 |
| HD (mJy) | $5.3 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | $1.21 \times 10^{-3}$ |
| LiH (mJy) | 2.1 | 4.8 | 43.3 |
| CO (mJy) | $3.6 \times 10^{-2}$ | $8.2 \times 10^{-2}$ | $73.0 \times 10^{-2}$ |
| dust cont. at 0.11 mm (mJy) | $3.9 \times 10^{-6}$ | $8.8 \times 10^{-6}$ | $7.9 \times 10^{-5}$ |
| dust cont. at 0.67 mm (mJy) | 0.075 | 0.17 | 1.52 |
| dust cont. at 2.60 mm (mJy) | $2.2 \times 10^{-2}$ | $4.9 \times 10^{-2}$ | 0.44 |