A PREDICTION OF BROWN DWARFS IN ULTRACOLD MOLECULAR GAS

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ABSTRACT

A recent model for the stellar initial mass function (IMF), in which the stellar masses are randomly sampled down to the thermal Jeans mass from hierarchically structured prestellar clouds, predicts that regions of ultracold CO gas, such as those recently found in nearby galaxies by Allen and collaborators, should make an abundance of brown dwarfs with relatively few normal stars. This result comes from the low value of the thermal Jeans mass, which scales as $M_J \propto T^2/P^{1/2}$ for temperature $T$ and pressure $P$, considering that the hierarchical cloud model always gives the Salpeter IMF slope above this lower mass limit. The ultracold CO clouds in the inner disk of M31 have $T \sim 3$ K and pressures that are probably 10 times higher than in the solar neighborhood. This gives a mass at the peak of the IMF equal to 0.01 $M_\odot$, well below the brown dwarf limit of 0.08 $M_\odot$. Using a functional approximation to the IMF given by $[1 - e^{-(M/M_\star)^2}]M^{-1.35}\ln M$ for $M > M_\star$, which fits the local IMF for the expected value of $M_\star \sim 0.3$ $M_\odot$, an IMF with $M_\star = 0.01$ $M_\odot$ in M31 has 50% of the mass and 90% of the objects below the brown dwarf limit. The brightest of the brown dwarfs in M31 should have an apparent extinction-corrected K-band magnitude of $\sim 30$ mag in their pre-main-sequence phase. For typical star formation efficiencies of $\lesssim 10\%$, brown dwarfs and any associated stars up to $\sim 2.5$ $M_\odot$ should not heat the gas noticeably, but if the IMF continues up to arbitrarily high masses, then the star formation efficiency must be $\lesssim 10^{-4}$ to avoid heating from massive stars.

Subject headings: ISM: general — stars: formation — stars: low-mass, brown dwarfs — stars: luminosity function, mass function

1. INTRODUCTION

The recent observation of ultracold CO in the inner disk of M31 by Allen et al. (1995), and the inference that ultracold CO exists in some spiral-arm dust lanes where neither CO nor H I have been detected in spite of a large dust extinction (M83: Allen, Atherton, & Tilanus 1985; Tilanus & Allen 1993; M51: Tilanus & Allen 1989; M100: Rand 1995; M81: Allen et al. 1997) lead us to wonder about the form of the initial mass function (IMF) for any stars that are born at such low temperatures. Here we propose that star formation in ultracold gas is biased toward brown dwarfs, and we show that these objects, along with the stars that are likely to form with them, could have escaped detection up to now because they do not heat the gas enough to raise the temperature to normal levels, nor do they appear as stellar objects in existing images.

In the solar neighborhood, brown dwarfs are so uncommon that the IMF cannot continue to rise below about 0.1 $M_\odot$ (Zuckerman & Becklin 1992; Pound & Blitz 1993, 1995; Reid & Gaziz 1997a, 1997b). The number of possible brown dwarfs is consistent with an extension of the IMF flattening seen between $\sim 1$ and $0.4$ $M_\odot$ (Reid 1998). The relative number of brown dwarfs could be much higher in the ultracold gas of M31, however. The detection of numerous brown dwarfs there would be an important confirmation of recent IMF models.

2. THE CASE FOR UNIFORMITY IN THE IMF

The IMF is observed to be remarkably uniform from region to region in any one galaxy (see reviews in Massey 1998; Elmegreen 1999a), covering star formation that spans a factor of $\sim 200$ in density (Massey & Hunter 1998; Luhman & Rieke 1998) and a factor of $\sim 10$ in metallicity (Freedman 1985; Massey, Johnson, & DeGioia-Eastwood 1995). It is also about the same in different H II regions in various galaxies (Bresolin & Kennicutt 1997) and in many different galaxies on average (Kennicutt, Tamblyn, & Condon 1994), as indicated by the equivalent widths of hydrogen emission lines. Detailed studies of color-magnitude diagrams in the LMC and local dwarf galaxies give the same IMF as well (Greggio et al. 1993; Marconi et al. 1995; Holtzman et al. 1997; Grillmair et al. 1998).

There is apparently also some uniformity in the IMF with time, since stars with a wide range of ages in our Galaxy all have about the same function, as suggested by halo stars (Nissen et al. 1994) and globular cluster stars (De Marchi & Paresce 1997). Similarly, a nearly universal IMF was found from abundance ratios (e.g., Fe/O, reflecting the ratio of low-mass to high-mass supernova processing) in QSO damped Ly$\alpha$ (Lu et al. 1996) and Ly$\alpha$ forest (Wyse 1998) lines, the intracluster medium (Renzini et al. 1993; Wyse 1997, 1998; but see Loewenstein & Mushotzky 1996), and elliptical galaxies (see review in Wyse 1998).

An IMF biased toward high-mass stars has been suggested for starburst regions, based on the ratio of luminous to dynamical mass (Rieke et al. 1980, 1993; Kronberg, Biermann, & Schwab 1985; Wright et al. 1988), galactic evolution models (Doane & Matthews 1993), spectroscopic line ratios (Doyon, Joseph, & Wright 1994; Smith et al. 1995), and infrared excesses (Smith, Herter, & Haynes 1998). However, a lower extinction correction for M82 makes the IMF there normal (Devereux 1989; Satyapal et al. 1995, 1997), and more recent evolutionary models (Schaerer 1996), multiwavelength spectroscopy and broadband infrared photometry (Calzetti 1997), and emission line spectroscopy (Stasińska & Leitherer 1996) give normal IMFs as well. Large IMF shifts in starburst galaxies should also produce unobserved red populations of stars after the turnover age reaches the stellar lifetime at the truncation...
mass (Charlot et al. 1993), and too high an oxygen abundance (Wang & Silk 1993).

An IMF shift toward lower mass stars has been reported for the extreme field by Massey et al. (1995). However, this result could also come from a normal IMF in each star-forming region if massive stars form preferentially in high-mass clouds and stop further star formation when they do (Elmegreen 1999b). The extreme-field IMF cannot be typical, because the IMFs in most clusters and associations are about the same as the galaxy-integrated IMFs.

There are also IMF dips, gaps, and a \( \pm 0.5 \) cluster-to-cluster variation in the power-law slope (Scalo 1998), but such variations are expected statistically given the small numbers of stars that are usually included in cluster studies (Elmegreen 1999b).

There are few theoretical predictions of IMF variations. Fabian (1994) predicted that the IMF would be biased toward low-mass stars at the cores of galaxy cluster cooling flows because of the low Jeans mass that results from the expected high pressures there. Larson (1998) proposed that a top-heavy IMF in the early universe could explain the G-dwarf problem, the high temperature and high metal abundance of intracluster gas, and the large luminosities of young elliptical galaxies. Neither of these predictions have been directly confirmed, however.

In what follows, we discuss the possible dependence of the minimum stellar mass on cloud temperature and pressure. First we discuss the minimum mass in general terms, and then we apply the results to ultracold clouds in M31.

3. THE THERMAL JEANS MASS AS A LIMIT TO STELLAR MASS

A lower mass limit is required for star formation because cloud pieces in prestellar clouds extend down to masses much smaller than the smallest stellar mass. Clumps with masses as low as \( 10^{-4} M_\odot \) have been observed in great abundance as part of the normal, power-law clump mass function in the Polaris spur (Heithausen et al. 1998; Kramer et al. 1998). This means that the stellar mass range is only a small part of the total mass range for cloud clumps, and that there must be some physical process that limits the stellar mass at the low end.

One possibility is that the minimum stellar mass is proportional to the thermal Jeans mass,

\[
M_J = 0.35 \left( \frac{T}{10^4 \text{K}} \right)^2 \left( \frac{P}{10^6 k_B} \right)^{-1/2} M_\odot ,
\]

for temperature \( T \) and cloud core pressure \( P \). In this model, cloud pieces much smaller than \( M_J \) are not likely to become stars because they are not strongly self-gravitating (Larson 1992; Elmegreen 1997, 1999b).

The mass of a star that actually forms in such a minimum unstable cloud piece can be smaller than \( M_J \), perhaps by a factor of 10, because not all of the gas goes into stars, and because the resulting stellar system could be binary, in which case the stars would have to share the clump mass. For this reason, \( M_J \), or some factor of order unity times \( M_J \), is identified with the mass at the break point in the IMF, where the power law first becomes flat, not with the minimum mass of a star. This is because the model only predicts a fundamental change in the physical properties of cloud clumps at this mass, but does not specify how the stars actually form inside the clumps. Indeed, stellar masses are often observed to continue down to at least one-quarter of the mass of the break point, but such stars are not as common as would be expected from an extrapolation of the Salpeter power-law function.

The expression for \( M_J \) is the Bonner-Ebert condition for stability of a nonmagnetic, pressure-bounded, isothermal sphere. Magnetic forces increase this critical mass (e.g., Mouschovias & Spitzer 1976), so they should not be included in the minimum value. In addition, the mass-to-flux ratio varies in a turbulent cloud as a result of random compressions and magnetic diffusion, so regions with large mass-to-flux ratios will develop spontaneously and systematically over time, suggesting again that equation (1), without magnetic fields, is the proper condition (see also Nakano 1998).

The numerator in \( M_J \) contains the thermal temperature, rather than the turbulent rms speed, because turbulence increases the critical mass, and because the smallest stars will generally form on such small scales that the relative turbulent speed is less than the sound speed anyway. The pressure in the expression for \( M_J \) is the total pressure at the boundary of the isothermal sphere. This pressure is not well defined for a real cloud because it comes partly from turbulent interclump motions and partly from thermal pressure in the interclump and overlying media (e.g., Hunter & Fleck 1982; Ballesteros-Paredes, Vazquez-Semadeni, & Scalo 1999). The value for any particular cloud is not well defined either, because pressure varies from place to place. Nevertheless, the total pressure is much more uniform in a cloud than either the turbulent or the thermal pressures alone, which interchange roles during transient compressions, and is also more uniform than the density, because of the Larson (1981) scaling relations, which make \( \rho \Delta v^2 \sim \text{constant} \) for density \( \rho \) and rms speed \( \Delta v \). In Taurus-like clouds, \( P \sim 10^5 k_B \); in GMCs, \( P \sim 10^6 k_B \); and in cluster-forming GMC cores, \( P \sim 10^7 k_B \).

These differences in \( P \) suggest that the IMF may differ as well, which means that the lowest mass stars in GMCs might be smaller than the lowest mass stars in Taurus-like clouds. Any such differences would not be large, however, because of the square-root dependence of \( M_J \) on \( P \). Small IMF differences would not have been recognized either. Most stars form in GMCs under similar conditions, so their local IMFs are similar. Where the conditions differ, as in Taurus, there are too few stars to get an accurate IMF. In addition, the expected decrease in the mass at the peak of the IMF for dense GMC cores is offset by stellar mass segregation (a concentration of massive stars near the center) and by a slightly increased temperature from nearby OB stars.

Strong variations in \( M_J \) are not expected on a galactic scale, either. The numerator in \( M_J \) is roughly proportional to the cloud cooling rate, and the denominator is roughly proportional to the background galactic heating rate from stars and cosmic rays (Elmegreen 1997; 1999b). Thus, molecular clouds in equilibrium will all have about the same \( M_J \), as long as the galactic mass-to-light ratio is about the same (expected variations in the IMF with \( M/L \) are discussed in Elmegreen 1999c).

The transition from the power-law part of the IMF to the low-mass turnover should contain important information about the star formation process, unlike the power-law part itself, which theory suggests contains only information about hierarchical cloud structure, i.e., about the initial con-
ditions for star formation. The mathematical form for this transition, i.e., the way in which the lower mass limit actually affects the shape of the IMF, cannot yet be determined from theory. We have approximated this form simply by writing a probability \( P_f \) that a cloud piece fails to form a star on a timescale comparable to its internal crossing time. The functional form of this probability is unknown (cf. eq. [3]), so the exact value of the minimum critical mass cannot be known yet either. Differences of a factor of 3 in the definition for \( M_\text{f} \) can easily be compensated for by differences in the form of \( P_f \). Nevertheless, the concept that thermal pressure in a star-forming cloud ultimately limits the mass of a star is an essential part of the model, and leads to a characteristic mass at the low end of the IMF that should scale with \( T^2/P^{1/2} \).

The lower mass limit comes from another source in an alternative IMF model, which follows from ideas by Larson (1982) and Shu, Adams, & Lisano (1987), namely, that protostellar winds limit the accretion onto a star and thereby set the final stellar mass at a value close to the lower limit necessary to drive such a wind (Nakano, Hasegawa, & Norman 1995; Adams & Fatuzzo 1996). The wind-limited mass is not the same as the deuterium-burning limit itself, so the exact value of the minimum critical mass cannot be determined analogously to that in M31. The stellar blue surface brightness and the nonthermal radio continuum flux are lower than in the inner Milky Way, probably as a result of the earlier Hubble type for M31. This implies that radiative and cosmic-ray heating rates are low, so the molecular gas equilibrates at a lower temperature, around 3.5 K (Allen et al. 1995; Loinard & Allen 1998). In that case, there is a factor of \(~3\) drop in the temperature of potential star-forming material for the ultracold CO gas in M31, and, when combined with the expected higher pressure, a resulting net decrease in \( M_\text{f} \) by a factor of \(~30\). This gives a value of

\[
M_\text{f} \sim 0.01 \, M_\odot
\]

in the inner-disk dark clouds of M31. If the pressure is the same in the cloud cores as it is locally, then \( M_\text{f} \sim 0.03 \, M_\odot \). Observation of a significant population of \(~0.01–0.1 \, M_\odot\) stars and brown dwarfs in the inner dark clouds of M31 would therefore support theories of the IMF based on either the thermal Jeans mass limit or the thermal accretion rate limit for the lowest mass star.

The random-sampling model also predicts that the slope of the IMF above the thermal Jeans mass should be independent of \( T, P, \) and other cloud properties, since clouds presumably partition themselves in a standard way by turbulence (for a discussion of cloud structure and turbulence, see Falgarone, Phillips, & Walker 1991). We expect the same Salpeter slope, namely, \(-1.35\) on a log-log plot, for stars with \( M \gg 0.01 \, M_\odot \) in the M31 inner dark clouds, as we find in the intermediate- to high-mass parts of the IMF measured locally. A simulation showing this independence between the high-mass slope and \( M_\text{f} \) was shown by Figure 4 of Elmegreen (1997). Thus, the random-sampling model predicts that the IMF in ultracold clouds should be exactly shifted toward lower mass without any change in the slope of the power-law part.

The observed IMF can be approximated by the function

\[
\log(n_\text{log}(M))d\log M \approx A [1 - e^{-(M/M_\odot)^{\alpha}}] M^{-1.35}d\log M
\]

for constant \( A \) and for \( \alpha \) in the range from 1 to 2; \( \alpha \approx 1 \) for an IMF that flattens at low mass and \( \alpha \approx 2 \) for an IMF that turns over at low mass. There are only a few observations.
yet of a low-mass turnover on a log-log plot (Reid & Gaziz 1997a; Hillenbrand 1997; Nota et al. 1998), but numerous observations show a flattening. Note that there are usually many stars in this flattened region, and that the minimum stellar mass can be as low as one-quarter the mass at the turnover point. In the model, $\alpha$ appears only in the probability for failure to form a star $[P_\alpha \propto e^{-\alpha(M/M_\odot)^{\alpha}}]$.

Equation (3) can be integrated to give the total stellar mass in various mass ranges. If $M_1 = 0.01 M_\odot$ and the brown dwarf limit is $M_{BD} \approx 0.08 M_\odot$, then $0.479$ of all the mass in various mass ranges. If and the will be in the form of brown dwarfs mass will be between and

Approximately $M$ in ultracold CO clouds, then the dust luminosity must be (Haas et al. 1998). If the dust and gas are thermally coupled with dust temperature as radiation heats the gas, then the stellar luminosity per unit formation efficiency is 1% and a high fraction of the stellar energy for failure to form a star $\ll 1/3000 \times$ the local value, so the dust and gas

nosity to mass equal to 6.4 $\times 10^{-4}$ ergs $s^{-1}$ g$^{-1}$. If the ratio of the stellar luminosity that heats the gas divided by the gas mass, $(L/M)_y$ from brown dwarfs and other young stars is close to this, then the gas would not be supercold. A typical $L/M$ for pre-main-sequence brown dwarfs is $\sim 1$ in these units (D’Antona & Mazzitelli 1994), so if the star formation efficiency is 1% and a high fraction of the stellar radiation heats the gas, then the stellar luminosity per unit total mass would be 0.01 ergs $s^{-1}$ g$^{-1}$, which is 16 times larger than the ratio needed to heat the cloud to 10 K.

Most embedded stellar radiation does not go into the gas directly, however; it goes into the dust, which radiates it away in the IR. The dust luminosity scales approximately with dust temperature as $T^3$ (e.g., Hollenbach & McKee 1979), and a typical cold dust temperature in M31 is $\sim 16$ K (Haas et al. 1998). If the dust and gas are thermally coupled in ultracold CO clouds, then the dust luminosity must be less in $\sim 3$ K clouds than it is locally by a factor of about $5^3 \sim 3000$. The background radiation field in M31 is brighter than 1/3000 times the local value, so the dust and gas cannot be well coupled in the M31 ultracold CO clouds. This means that the average gas density in these clouds is much less than $\sim 10^4$ cm$^{-3}$. The density is higher than this in star-forming cores, but these are shielded from outside light by dust, so the core dust temperature should be low there.

The likely range for the average cloud density can be estimated from the inclination-corrected column density of $\sim 100 M_\odot$ pc$^{-2}$ (Loinard & Allen 1998). Considering a typical cloud projected size of $\sim 100$ pc, the cloud thicknesses are probably somewhere between $\sim 1$ pc, if they are thin shells, and $\sim 100$ pc, the thickness of the galaxy. This puts the average cloud density between 1 and 100 $M_\odot$ pc$^{-3}$, which corresponds to a molecular hydrogen density of 15–1500 cm$^{-3}$. This is consistent with the result of Loinard, Allen, & Lequeux (1996), who estimated a density of $\sim 100$ cm$^{-3}$ from CO line ratios. Thus, the average density is indeed too low for thermal coupling between the gas and dust.

A better way to determine whether embedded brown dwarfs can significantly heat ultracold CO is to compare the summed luminosities of these stars to the incident and embedded luminosity from field stars. If the brown dwarf luminosity in the clouds is less than the total absorbed field star power, then the clouds would not show any excess emission in either dust or gas from the embedded young stars.

The total field star power received by a spherical cloud of radius $R$ is

$$P_f = 4\pi R^2 j_f (\pi \lambda + R/3)$$

for field star volume emissivity $j_f$ and average path length $\lambda$ for field star radiation. The first contribution in the parenthesis is from external field stars, and the second is from internal field stars. The total luminosity of embedded young stars with volume emissivity $j_y$ is

$$L_y = (4/3)\pi R^3 j_y.$$ (5)

The ratio $L_y/P_f$ must be large for the cloud temperature to increase significantly as a result of embedded star heating. This ratio gives a critical ratio of volume emissivities

$$j_y / j_f > 1 + 3\pi \lambda \overline{R} \sim 10^2 - 10^3$$

for embedded star heating; here we have taken an external path length equal to 10–100 times the cloud size, considering this as the ratio of cloud mean free path to size, or the inverse of the volume filling factor of these ultracold CO clouds.

The volume emissivity of embedded stars is $j_y = (L/M)_y \epsilon \rho$ for average stellar luminosity-to-mass ratio $(L/M)_y$, star formation efficiency $\epsilon$ (the ratio of the star mass to the total cloud mass), and gas density $\rho$. To find the average $(L/M)_y$, as a function of time, we integrate the pre-main-sequence stellar luminosities over the stellar mass function,

$$\left( {L \over M} \right)_y(t) = \int_{M_0}^{M_U} L(M, t) n(M) dM \int_{M_0}^{M_U} M n(M) dM ,$$

using the Alexander + Rogers & Iglesias CM model for $L(M, t)$ in D’Antona & Mazzitelli (1994) and $n(M) dM = n_0(M) dM$ from equation (3). These pre–main-sequence models are only for $M < M_U = 2.5 M_\odot$, so our results are valid only in this limit. Equation (7) gives $(L/M)_y$ for a time $t$ after a short burst of star formation. To get $(L/M)_y$ from continuous star formation that has lasted for a time $t$, we use

$$\left( {L \over M} \right)_{y, cont}(t) = \int_0^t dt \int_{M_0}^{M_U} {L(M, t) \rho(M) dM \over \int_0^t dt \int_{M_0}^{M_U} M \rho(M) dM }$$

for star formation rate by number $\rho(M)$, which is proportional to $n(M)$ for a uniform star formation rate. The lower limits to these integrals are taken to be $M_1$ instead of the absolute minimum stellar mass, because the form of the IMF is not well known below the peak and because lower mass brown dwarfs should not contribute much to the luminosity anyway.

The burst and continuous $(L/M)_y$ are shown in Figure 1 as functions of time since the burst and as functions of age, respectively, for $M_1 = 0.01 M_\odot$ and for mass ranges 0.02–1 and 0.02–2.5 $M_\odot$. For continuous star formation, $(L/M)_y \sim 2 L_\odot/M_\odot \sim 4$ ergs $s^{-1}$ g$^{-1}$ for this IMF. For the larger mass range, the burst $(L/M)_y$ levels off because massive stars dominate the light and reach the main sequence after $\sim 10^6$ yr.
The background stellar density in the inner M31 disk is several \( M_\odot \) pc\(^{-3}\), and the density in the ultracold CO clouds is in the range \( 1-100 \) \( M_\odot \) pc\(^{-3}\) given above, so \( \rho/\rho_f \sim 0.5-50 \). This is comparable to the critical density ratio for young star heating only if \( \epsilon > 0.1 \).

*We conclude that a brown dwarf + stellar population with \( M < 2.5 M_\odot \) would not heat the ultracold CO clouds in M31 noticeably if the star-to-cloud mass ratio is less than 10%.*

Another way to get a limit on how many brown dwarfs and other young stars might be present is from a limit on the mass of the most massive star that can be associated with these clouds. The largest stellar mass, \( M_{\text{max}} \), that is likely to come from an IMF with a total stellar mass \( M_{\text{tot}} \) is given by

\[
\frac{\int_0^{\infty} M n(M) dM}{\int_{M_{\text{max}}}^{\infty} n(M) dM} = M_{\text{tot}}. \tag{10}
\]

Figure 2 (solid lines, left axis) shows the total stellar and brown dwarf masses versus \( M_{\text{max}} \) (the two lines nearly overlap). If the largest pre-main-sequence or stellar mass that can be hidden in and around the ultracold CO clouds in M31 is \( \sim 2 M_\odot \), then the total mass of all the brown dwarfs + stars must be less than \( \sim 50 M_\odot \). Figure 2 (dashed lines, right axis) shows the numbers of brown dwarfs (upper dashed line) and stars as functions of \( M_{\text{max}} \). With \( M_f \sim 0.01 M_\odot \), there could be \( \sim 10^3 \) brown dwarfs and \( \sim 10^2 \) stars less massive than 2.5 \( M_\odot \) in each of the large ultracold CO clouds in M31.

6. A LOW STAR FORMATION RATE

This number of \( \sim 10^3 \) hidden brown dwarfs in ultracold CO clouds may seem large compared to what has been found so far in the solar neighborhood, but the associated number of normal stars and the total mass in the form of stars or brown dwarfs is remarkably small for such a cloud with an estimated \( \sim 10^6 M_\odot \) of gas (Loinard & Allen 1998). If the efficiency of star + brown dwarf formation is anything like it is locally, namely, \( \geq 1\% \), then so many stars should have formed that the IMF would have sampled out far enough into the high-mass tail to produce O-type stars, which would be seen easily. This implies that star formation is unusually inefficient in the M31 ultracold CO clouds.

One possible explanation for this is that the clouds are much less dense than the excitation densities given by Loinard & Allen (1998). These authors found, on the basis of excited-state CO line ratios, that the gas is optically thick in the 3-2, 2-1, and 1-0 \(^{12}\)CO lines. In that case, the density required for excitation is less by the factor \( 1/\epsilon \) for opacity \( \tau \) than the density that makes the collision rate equal to the spontaneous transition rate \( A \). Thus, the molecular density can be \( \sim 10 \) times less than their estimate, and the clouds much less strongly self-gravitating. If the clouds are like Galactic translucent clouds, they may form no stars at all (e.g., Hearty et al. 1999).

We can use the example provided by M31 to estimate the importance of brown dwarf formation generally. Suppose the efficiency of brown dwarf + star formation in ultracold gas is the upper limit given by the M31 clouds, which is \( \sim 10^{-4} \) in \( 10^6 M_\odot \) clouds, to avoid stars more massive than 2 \( M_\odot \). Suppose also that half the stellar-like mass goes into brown dwarfs and that the ages of the ultracold clouds are...
at least $\sim 10^7$ yr, which is a modest fraction of the shear time in the inner disk M31. Then the brown dwarf formation rate is $<5 M_\odot$ Myr$^{-1}$ per $10^6 M_\odot$ of ultracold gas. This implies a gas consumption time that is very large, $2 \times 10^4$ yr, which means hardly any conversion of gas into stars or brown dwarfs in a Hubble time. To get a significant mass in brown dwarfs, the efficiency of star formation must be larger than this by a factor of $\sim 100$, but then the resulting luminosity would heat an ultracold cloud to normal temperatures, shutting off brown dwarf production in favor of regular stars.

The formation of brown dwarfs in ultracold gas requires a negligible mass of normal stars, so that the gas remains cold. This would occur naturally in the lowest mass clouds from an ensemble of clouds if the stars formed randomly. For example, if the maximum total mass that can form in a cloud before a massive star is likely to heat the gas is $\sim 100 M_\odot$, from Figure 2, and if the efficiency is large, 10%, then the clouds that make brown dwarfs must be smaller than $10^3 M_\odot$. Such small clouds are rarely isolated, however, and nearby gas can still make massive stars that provide heat. Thus, is it unlikely that brown dwarfs can form with a significant total mass if the IMF is simply shifted toward a lower peak mass with a Salpeter spectrum above this. An upper mass cutoff in star formation, which is not present in the theory, would seem to be necessary if brown dwarfs are ever found to dominate the mass in a region.

7. CONCLUSIONS

The ultracold clouds in M31 provide a good test for theories of the IMF. Because of their low temperatures and normal-to-high pressures, these clouds should have a thermal Jeans mass of only $\sim 0.01 M_\odot$, making the IMF shift toward lower mass with the same slope at higher mass. In that case, ultracold clouds should produce half of their stellar-like mass in the form of brown dwarfs. If the total number of such dwarfs per cloud is $\lesssim 10^2$, then they and their accompanying H-burning stars would not significantly heat the cloud, nor would they be visible in existing surveys. A deep K-band search for brown dwarfs in ultracold gas would be necessary to see them. Considering the luminosities of such pre-main-sequence stars found locally, which is $K \sim 13$ mag dereddened (Luhman et al. 1998), the K-band luminosity of such a star in M31 would be $\sim 30$ mag plus extinction.

Helpful comments by the referee are appreciated.