Feedback from the infrared background in the early Universe

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ABSTRACT
It is commonly believed that the earliest stages of star formation in the Universe were self-regulated by global radiation backgrounds – either by the ultraviolet (UV) Lyman–Werner (LW) photons emitted by the first stars (directly photodissociating H2), or by the X-rays produced by accretion on to the black hole (BH) remnants of these stars (heating the gas but catalysing H2 formation). Recent studies have suggested that a significant fraction of the first stars may have had low masses (a few M⊙). Such stars do not leave BH remnants and they have softer spectra, with copious infrared (IR) radiation at photon energies ∼1 eV. Similar to LW and X-ray photons, these photons have a mean-free path comparable to the Hubble distance, building up an early IR background. Here we show that if soft-spectrum stars, with masses of a few M⊙, contributed ≳0.3 per cent of the UV background (or their mass fraction exceeded ∼80 per cent), then their IR radiation dominated radiative feedback in the early Universe. The feedback is different from the UV feedback from high-mass stars, and occurs through the photodetachment of H− ions, necessary for efficient H2 formation. Nevertheless, we find that the baryon fraction which must be incorporated into low-mass stars in order to suppress H2 cooling is only a factor of a few higher than for high-mass stars.

Key words: molecular processes – stars: Population III – galaxies: formation – cosmology: theory – early Universe.

1 INTRODUCTION

In hierarchical models of structure formation, the first stars in the Universe form in dark matter (DM) minihaloes with masses of ∼10⁵ M⊙ at redshifts of z ∼ 20–30, through efficient cooling of the gas by H2 (Haiman, Thoul & Loeb 1996; see a comprehensive review by Barkana & Loeb 2001). However, soon after the first stars appear, early radiation backgrounds begin to build up, resulting in feedback on star formation. In particular, the ultraviolet (UV) radiation in the Lyman–Werner (LW) bands of H2 can photodissociate these molecules and suppress gas cooling, possibly preventing star formation (Haiman, Rees & Loeb 1997; Omukai & Nishi 1999; Ciardi, Ferrara & Abel 2000; Haiman, Abel & Rees 2000; Machacek, Bryan & Abel 2001; Ricotti, Gnedin & Shull 2001, 2002; Mesinger, Bryan & Haiman 2006, 2009; Wise & Abel 2007, 2008a,b; Johnson, Greif & Bromm 2008; O’Shea & Norman 2008; Whalen et al. 2008).

Numerical simulations (e.g. Abel, Bryan & Norman 2002; Bromm, Coppi & Larson 2002; Yoshida et al. 2003) have long suggested that the metal-free stars forming in the early minihaloes were very massive (∼100 M⊙), owing to the rapid mass accretion enabled by H2 cooling. These stars would then leave behind remnant black holes with similar masses (Heger et al. 2003), and produce X-rays, either by direct accretion or by forming high-mass X-ray binaries. A soft X-ray background at photon energies of ∼1 keV, at which the early intergalactic medium (IGM) is optically thin, then provides further global feedback: both by heating the IGM and by catalysing H2 formation in collapsing haloes (Haiman, Rees & Loeb 1996; Oh 2001; Venkatesan, Giroux & Shull 2001; Glover & Brand 2003; Chen & Miralda-Escudé 2004; Madau et al. 2004; Ricotti, Ostriker & Gnedin 2005; Mirabel et al. 2011).

Recent simulations have been pushed to higher spatial resolution, and in some cases, using sink particles, were able to continue their runs beyond the point at which the first ultradense clump developed. The gas in the central regions of at least some of the early minihaloes was found to fragment into two or more distinct clumps (Turk, Abel & O’Shea 2009; Stacy, Greif & Bromm 2010; Clark et al. 2011; Greif et al. 2011; Prieto et al. 2011). This raises the possibility that the first stars formed in multiple systems, and that many of these stars had lower masses than previously thought (but see Turk et al. 2012, for still higher resolution simulations that suggest less efficient fragmentation).

There is also some observational evidence suggesting a lower characteristic Population III (Pop III) mass. Massive (∼140 M⊙), non-rotating, metal-free stars are expected to end their lives as
pair-instability supernovae (PISNe), and the non-detection of the characteristic PISN nucleosynthetic patterns in metal-poor stars suggests that the typical Pop III stars did not form with such high masses (see e.g. a recent review by Frebel & Norris 2012). The observations of carbon-enhanced metal-poor stars may further imply a significant number of Pop III stars with masses as low as $M = 1-8 \, M_\odot$ (Tumlinson 2007a,b). Finally, the recent discoveries of extremely metal-poor stars with no sign of C or N enhancement show that low-mass star formation could occur at metallicities much lower than previously assumed (Caffau et al. 2011, 2012), likely facilitated by dust fragmentation (Schneider et al. 2012).

Motivated by the above, in this Letter we examine radiative feedback from an early cosmic infrared (IR) background, produced by a population of low-mass stars. Although we focus on low-mass Pop III (i.e. metal-free) stars, our conclusions are more generic, and apply at any cosmic epoch when significant numbers of low-mass Pop II stars co-exist with massive Pop III stars. Low-mass stars are expected to have soft spectra, even in the metal-free case (Tumlinson & Shull 2000; Marigo et al. 2001; Schaerer 2002), producing significant radiation at $2.2$ eV, near the photodetachment threshold (0.76 eV) of the H$^-$ ion. H$^-$ is a reactant in the dominant formation channel for H$_2$, (H$^-$ $+$ H $\rightarrow$ H$_2$ $+$ e$^-$) and its destruction can therefore have a dramatic impact on the thermal evolution of metal-free gas.

In fact, it is well known that photodetachment of H$^-$ by cosmic microwave background (CMB) photons kept the H$_2$ formation rate in the early Universe very low, until the CMB photons redshifted to lower energies at $z \sim 100$ (Hirasawa, Aizu & Taketani 1969; Hirata & Padmanabhan 2006). H$^-$ photodetachment can become globally important again once stars begin to form, if they have soft spectra.$^1$

The aim of this Letter is to quantify (i) if and when, due to low-mass stars, H$^-$ photodetachment again became the dominant process to limit H$_2$ cooling in the earliest protogalaxies, and (ii) to what extent this may have increased or decreased the net global negative radiative feedback in the early Universe. We focus on the importance of this negative feedback for minihaloes (as opposed to the more massive haloes that cool even in the absence of molecular hydrogen). In order to accomplish this, we perform ‘one-zone’ calculations, following the coupled chemical and thermal evolution of the gas in the presence of a cosmological radiation background, including H$^-$ photodetachment by IR photons and H$_2$ photodissociation by LW photons.

The rest of this Letter is organized as follows. In Section 2, we describe our chemical and thermal modelling. In Section 3, we present our results for the relative importance of IR radiative feedback, with various assumptions about the stellar populations; we also compare our results to previous studies. Finally, in Section 4 we offer our conclusions. Throughout this Letter, we adopt a standard CDM cosmological background model: ($\Omega_{DM}$, $\Omega_b$, $\Omega_\Lambda$, $\hbar$) = (0.233, 0.046, 0.721, 0.701) (Komatsu et al. 2011).

2 MODELLING

2.1 Background spectrum

We assume that the early Universe is filled with background radiation produced by stars. Massive metal-free stars have hard spectra, with effective blackbody temperatures of $T_{\text{eff}} \approx 10^4$ K on the zero-age main sequence (ZAMS), nearly independent of their mass above $M_\star \gtrsim 100 \, M_\odot$ (Bromm, Kudritzki & Loeb 2001; Marigo et al. 2001; Schaerer 2002). Below this mass, the effective temperature decreases monotonically, and reaches $T_{\text{eff}} \approx 10^4$ K at $M_\star \approx 2 \, M_\odot$ (Tumlinson & Shull 2000; Marigo et al. 2001; Schaerer 2002).

We first consider a composite spectrum produced by co-existing low- and high-mass stars, the relative abundances of which are allowed to vary. We choose characteristic masses of $M_\star = 1.2 \, M_\odot$ and $M_\star = 100 \, M_\odot$, which have time-averaged effective temperatures of $T_{\text{eff}, 100} = 10^{4.85}$ K and $T_{\text{eff}, \infty} = 10^{4.85}$ K, respectively (Marigo et al. 2001). These stars have main-sequence lifetimes of $t_{\text{ms}} \approx 3$ Gyr and $\approx 3$ Myr. In our analysis below, for low-mass stars with $t_{\text{ms}} < 0.5$ Gyr (the age of the Universe at $z \approx 10$), we reduce the total radiative output by the factor $(t_{\text{ms}}/0.5 \, \text{Gyr})$. We parametrize the population by the mass fraction of low-mass stars, $f_{\text{lo}}$, and also by their corresponding fractional contribution $f_{\text{lo}}^{\text{IR}}$ to the total UV radiation output (at 13.6 eV).

We caution that this is of course only a crude characterization of the true background – in principle, one needs to consider the time-evolving spectra of stars with a range of initial masses. Departures from a blackbody shape may also be important, as our results are sensitive to photons with the particular energies of $\sim 2$ eV (for H$^-$ detachment) and $\sim 12$ eV (for H$_2$ dissociation). However, given that the stellar initial mass function (IMF) is unknown, we here adopt this simple prescription and defer a more detailed treatment to future work. In order to understand the dependence on stellar mass, in Section 3.2 we repeat our calculations assuming the background is produced by stars with a single mass in the range $0.7 \leq M_{\star, \text{lo}} / M_\odot \leq 100$ (corresponding to effective temperatures in the range $6000 \lesssim T_{\text{eff}} \lesssim 10^5$ K).

The early IGM is optically thin at the IR energies of $\sim 2$ eV, relevant for photodetachment of H$^-$ (owing to the very low abundance of both intergalactic H$^-$ and of e$^-$). However, before reionization, the IGM is opaque above 13.6 eV, and we accordingly assume zero flux above this energy. UV photons in the LW bands (11.2–13.6 eV), travelling over cosmological distances, will also be absorbed by H$_2$ once they redshift into resonance with a Lyman line. This results in a ‘sawtooth modulation’ (Haiman et al. 1997), which reduces the H$_2$ dissociation rate by about an order of magnitude at $z = 15$ compared to the optically thin rate (Wolcott-Green & Haiman 2011). We include this reduction in our calculation. In principle, the optical depth in the LW lines due to intergalactic H$_2$ itself, with an abundance of $n_{\text{HI}} / n_H \sim 10^{-4}$, can be of the order of a few (Haiman et al. 2000; Ricotti et al. 2001; Kuhlen & Madau 2005); this additional opacity could further reduce the H$_2$ dissociation rate and would strengthen our conclusions; we conservatively ignore it in our calculations.

2.2 Chemistry and cooling

We model a static gas cloud which has condensed to the maximum density achievable by adiabatically collapsing in a minihalo with virial temperature $T_{\text{vir}}$: $\rho_{\text{max}} = f_{\text{J}} \rho_{\text{DM}} (T_{\text{vir}} / T_{\text{IGM}})^{3/2}$. Here $\rho_{\text{DM}}$ and $T_{\text{IGM}}$ are the density and temperature of the smooth background IGM, and $f_{\text{J}}$ (chosen below) is of the order of unity and is used for calibration against simulations. At this stage, only if sufficient H$_2$ forms will the cloud be able to radiatively cool and continue collapsing to higher densities, and ultimately form stars.

We follow the chemical and thermal evolution for primordial gas, using a standard chemical reaction network among nine species: H, H$^+$, H$^-$, He, He$^+$, He$^{2+}$, H$_2$, H$_2^+$ and e$^-$ (and photons).
Radiative cooling by H₂ is modelled as in Galli & Palla (1998). Our chemical model is adopted from Shang, Bryan & Haiman (2010), where the reader is referred to for more details and references. Updated rate coefficients are substituted for and are provided by Kreckel et al. (2010) and Steenrup, Larson & Elander 2009, respectively. We adopt initial conditions appropriate for a minihalo (i.e. with molecular hydrogen and electrons fractions of $x_{H_2} = 2 \times 10^{-6}$ and $x_e = 10^{-2}$, and initial gas temperature $T_{\text{gas}} = T_{\text{vir}} \approx 3 \times 10^3$ K). We follow the coupled thermal and chemical evolution using the stiff equation solver L-SODAR for $\approx 10^8$ yr (or $\sim 20$ per cent of the Hubble time at $z \sim 10$, after which it is likely the halo will have merged with another to form a larger collapsed object).

Photodetachment of H by continuum photons (H$^- + \gamma \rightarrow H + \text{e}^-$) is dominated by $\sim 2$ eV photons (at which the H$^-$ detachment rate peaks for $T_{\text{eff}} \approx 10^4$ K, slightly above the 0.755 eV threshold). We fit the frequency-dependent cross-section as in Shapiro & Kang (1987), convolving this with the blackbody spectrum to find the rate coefficient, parametrized as $k_{25} = 10^{-10} \alpha J_{21}$ s$^{-1}$. Here and below, $J_{21}$ denotes the specific intensity at the Lyman limit (13.6 eV) in units of $10^{-21}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Hz$^{-1}$. For the composite spectrum with $(T_{\text{eff},h} = 70$, $T_{\text{eff},b} = 10^4$ K, $T_{\text{eff},h} = 10^5$ K), we have $\alpha = \alpha_0 f_{\text{mass}}^{\text{Lo}} + \alpha_1 (1 - f_{\text{mass}}^{\text{Hi}})$ and $(\alpha_0, \alpha_1) = (10^7, 0.17)$.

For the photodetachment of H$_2$ by LW photons, we use the fitting formulae for the optically thick rate provided by Wolcott-Green, Haiman & Bryan (2011), which includes self-shielding as well as shielding by H$_1$. The column densities are specified by assuming the size of the collapsing region equals the Jeans length; however, we reduce $N_{\text{H}_2}$ by a factor of 2, which produces better agreement with the shielding found in three-dimensional simulations (Wolcott-Green & Haiman 2011).

### 3 RESULTS AND DISCUSSION

#### 3.1 Composite spectrum

**3.1.1 The critical flux**

To assess whether H$_2$ cooling can be suppressed by the IR background, we first run one-zone models at various different radiation intensities, normalized at the Lyman limit $J_{21}$. We employ a Newton–Raphson scheme to find the ‘critical flux’ $J_{\text{crit}}$ defined by requiring that the cooling time always remains longer than the dynamical time (equation 10 in Haiman et al. 1997). Repeating this calculation for haloes with different masses and redshifts, we have found that with the density normalization $f_0 \sim 2$, our resulting $J_{\text{crit}} = J_{\text{crit}}(M_{\text{halo}}, z)$ agrees well (to within a factor of 2) with the values and the mass- and redshift-dependence of $J_{\text{crit}}$ found in simulations (Machacek et al. 2001; Mesinger et al. 2006). Throughout this section, we show our results for a single halo mass scale, $T_{\text{vir}} \sim 10^4$ K and redshift $z = 18$. Apart from a monotonic overall increase of $J_{\text{crit}}$ with $T_{\text{vir}}$, our results are qualitatively the same for other redshift and halo masses (up to the scale corresponding to $T_{\text{vir}} \sim 10^4$ K, at which atomic cooling becomes important). It should be noted, however, that because self-shielding of H$_2$ is more important at higher halo masses, $J_{\text{crit}}(f_0 = 0)/J_{\text{crit}}(f_0 = 1)$ also increases with halo mass.

Our main result is shown in Fig. 1, the top panel of which shows the critical flux $J_{\text{crit}}$ as a function of $f_{\text{mass}}^{\text{Lo}}$ (the corresponding mass fraction $f_{\text{mass}}^{\text{Lo}}$ is shown along the upper horizontal axis). The critical flux decreases dramatically as $f_{\text{mass}}^{\text{Lo}}$ increases above the per cent level. Since the normalization of the critical flux is quoted at 13.6 eV, close to the LW band, the critical LW dissociation rate would be nearly independent of $f_{\text{mass}}^{\text{Lo}}$; the decrease is caused entirely by the

Figure 1. Top panel: the critical flux $J_{\text{crit}}$, required to suppress H$_2$ cooling as a function of $f_{\text{mass}}^{\text{Lo}}$. Here $f_{\text{mass}}^{\text{Lo}}$ is a proxy for the fraction of the Lyman limit flux contributed by low-mass stars with an effective temperature $T_{\text{eff}} \approx 10^4$ K (rather than high-mass stars with $T_{\text{eff}} \approx 10^5$ K). The corresponding mass fraction in the low-mass stars, $f_{\text{mass}}^{\text{Lo}}$, is shown along the upper horizontal axis. Bottom panel: the fraction of baryons that must be converted into stars in order to produce the critical flux shown in the top panel (solid line). Also shown is the required fraction if H$^-$ photodetachment is artificially switched off in the chemistry network (dashed line).

H$^-$ detachment by IR photons. The IR radiation becomes more important than the LW radiation when the decrease reaches a factor of 2, which occurs for $f_{\text{mass}}^{\text{Lo}} \approx 3 \times 10^{-3}$. However, because the low-mass stars emit far fewer Lyman limit photons than those with effective temperatures $< 10^4$ K, a mass fraction of $f_{\text{mass}}^{\text{Lo}} \approx 0.8$ is required to achieve even this smaller than per cent level contribution to the flux (as shown by the upper horizontal axis). For reference, the mass fraction of stars in the 0.1–1.2 M$_\odot$ (0.1–2 M$_\odot$) range for the commonly used Chabrier IMF is 86 per cent (94 per cent). In the limit of purely low-mass stars, $J_{\text{crit}}$ is decreased by a factor of $\sim 320$. [Note that Clark et al. (2011) do find the protostellar IMF peaked at $\lesssim 1$ M$_\odot$, but ZAMS masses are unknown.]

**3.1.2 Global impact**

We next ask whether the critical flux $J_{\text{crit}} = \text{few} \times (10^{-3}–10^0)$ can be produced by the mixture of high- and low-mass stars. To answer this, we determine the fraction of baryons that must be incorporated into stars to produce a given $J_{\text{crit}}$, as a function of $f_{\text{mass}}^{\text{Lo}}$. The energy density in LW photons $u_{\gamma} \approx 4\pi n_{\gamma} c / \text{c}$ is converted to a stellar mass density $\rho_*$ by computing the number of LW photons emitted per stellar baryon.$^2$ We use the data from Marigo et al. (2001) for this purpose, and find the mass-weighted average for the high- and low-mass populations.

The bottom panel of Fig. 1 shows the critical baryon fraction, $f_{\text{crit}}/f_{\text{mass}}^{\text{Lo}}$, which must be incorporated into stars to achieve $J_{\text{crit}}(f_{\text{mass}}^{\text{Lo}})$.

$^2$ We assume a flat spectrum across the narrow LW bands; the ‘sawtooth modulation’ by the IGM has been absorbed into $J_{\text{crit}}$. 

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(normalized to its value in the absence of any low-mass stars). The fraction varies relatively little over the range \(0 \leq f_{\text{LV}}^{\text{UV}} \leq 1\) (solid curve). The factor of \(\sim 5\) increase as \(f_{\text{LV}}^{\text{UV}} \rightarrow 1\) is due almost entirely to the long lifetimes of the low-mass stars and the corresponding reduction of their radiation output over the finite 0.5 Gyr age of the Universe (at \(z \approx 10\)). The otherwise near flatness of this curve is a coincidence: increasing \(f_{\text{LV}}^{\text{UV}}\) decreases both the critical flux and the production of LW photons per stellar mass, and these two factors turn out to nearly cancel. The bottom line is that \(H^+\) photodetachment can indeed suppress subsequent star formation; this requires converting baryons into low-mass stars up to five times more efficiently than in the high-mass case. Finally, the dashed curve in the bottom panel in Fig. 1 shows that if the IR photons from the low-mass stars were neglected, the required stellar density would increase by two orders of magnitude. This highlights the importance of including IR feedback in future models if the Pop III IMF indeed extends to such low masses (and also at all cosmic epochs when Pop II stars are already present).

3.2 Dependence on effective temperature

How low do the masses of low-mass stars need to be before IR feedback becomes important? To answer this question, we next consider stellar populations with a single effective temperature, in the range \(6000 \leq T_{\text{eff}} / \text{K} \leq 10^4\), and compute how \(J_{\text{crit}}\) and \(f_{\text{crit}}\) depend on \(T_{\text{eff}}\). The top panel of Fig. 2 shows a dramatic drop in the critical flux owing to the copious \(\sim 2\) eV photon output below \(T_{\text{eff}} \approx 1.5 \times 10^4\) K, or \(M \lesssim 2 M_{\odot}\). As shown in the bottom panel of this figure, the density in stars required to produce \(J_{\text{crit}}\) remains essentially constant down to this \(T_{\text{eff}}\), and very near the value required for LW feedback by high-mass stars. This flatness again results from the cancellation of two effects: the critical flux and the LW photon output (per stellar baryon) both decrease significantly as \(T_{\text{eff}}\) drops below \(1.5 \times 10^4\) K.

3.3 Comparison to previous studies

To our knowledge, the dominant importance of the radiation from low-mass stars for global star formation was not previously discussed or quantified, with the exception of Chuzhoy et al. (2007). These authors evaluated the global impact of \(H^+\)detachment by an IR background at later epochs, produced by recombination radiation as the IGM is becoming significantly ionized [Glover (2007) considered a similar scenario, with radiation from gas that is highly ionized by local sources]. They showed that if the ionization is produced by stars with a soft spectrum, as we consider here, the \(H^+\) detachment rate can be further boosted and can become globally important. However, they do not explicitly compare \(H^+\) and LW feedback, and do not answer the two questions addressed in this Letter: how many low-mass stars need to form (1) before \(H^+\) photodetachment becomes the dominant feedback mode, and (2) for this mode to become globally important.

Other previous works have touched on different aspects of the global radiative feedback discussed here. Examples include Mesinger et al. (2006, 2009), studying radiative feedback in a statistical sample of several hundred early minihaloes in cosmological simulations, Haiman et al. (2000) and Johnson et al. (2008), studying self-regulation of star formation in minihaloes through radiative feedback in semi-analytical models, and Whalen, Hückstaedt & McConkie (2010), studying radiative feedback in detailed hydrodynamical simulations with the stellar masses of the sources extending down to \(25 M_{\odot}\). However, in all of these works, feedback was due to LW (or ionizing UV) radiation.

Omukai (2001), Bromm & Loeb (2003), Shang et al. (2010), Wolcott-Green & Haiman (2011) and Wolcott-Green et al. (2011) have performed calculations similar to the one proposed here, including \(H^+\) photodetachment, but have focused on the more massive \((T_{\text{vir}} > 10^5\) K) atomic-cooling haloes. Because the gas in these haloes can cool via neutral H and reach high densities, a much larger flux \(J_{\text{crit}}\) is required to suppress \(H_2\) cooling. Nevertheless, these works have found results similar to the ones here: the critical flux for a soft spectrum is about one to two orders of magnitude lower than for a hard spectrum. For example, using three-dimensional simulations of three different haloes, Shang et al. (2010) found \(30 < J_{\text{crit}} < 300 (T_{\text{eff}} = 10^5\) K\) versus \(10^3 < J_{\text{crit}} < 10^5 (T_{\text{eff}} = 10^4\) K\). As found here, \(H^+\) detachment dominates in the former case, whereas \(H_2\) dissociation dominates in the latter. When self-shielding in the LW lines of \(H_2\) is modelled more accurately, however, this difference is reduced by about an order of magnitude (Wolcott-Green et al. 2011).

4 CONCLUSIONS

The main conclusion of this Letter is that if the mass fraction of low-mass (a few \(M_{\odot}\)) stars exceeded \(\sim 90\) per cent, then their early IR background radiation dominated over the LW background in suppressing \(H_2\) formation. This low-mass fraction is comparable to those in present-day IMFs, and it is interesting to note that in this limit star formation in minihaloes could be more efficient than if the early stars were massive, owing to the lack of UV feedback and heating inside haloes. The early IR background from the low-mass stars would then exert significant net feedback, and regulate the star formation history in the early Universe once a fraction \(f_s = \text{a few}\)
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\[ f_{\alpha, \text{LW}} \] of baryons were converted into stars. The threshold \[ f_{\alpha, \text{LW}} \] is the fraction required for strong LW feedback (from massive stars), which is \( \sim 10 \times f_{\text{esc}}^{\text{-1}} \) per cent that required for reionization assuming an escape fraction of ionizing photons, \( f_{\text{esc}} \), and \( n_{\gamma} = 10 \) ionizing photons per hydrogen atom. Future investigations of radiative feedback in the early Universe, which include low-mass stars, should therefore include H\(^-\) photodetachment. Our results also highlight the need for an accurate calculation of the IR photon output of low-mass stars.

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