DUSTY SUPERNOVAE RUNNING THE THERMODYNAMICS OF THE MATTER REINSERTED WITHIN YOUNG AND MASSIVE SUPER STELLAR CLUSTERS

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ABSTRACT

Following the observational and theoretical evidence that points at core-collapse supernovae (SNe) as major producers of dust, here we calculate the hydrodynamics of the matter reinserted within young and massive superstellar clusters under the assumption of gas and dust radiative cooling. The large SN rate expected in massive clusters allows for a continuous replenishment of dust immersed in the high temperature thermalized reinserted matter and warrants a stationary presence of dust within the cluster volume during the type II SN era. We first show that such a balance determines the range of the dust-to-gas-mass ratio, and thus the dust cooling law. We then search for the critical line that separates stationary cluster winds from the bimodal cases in the cluster mechanical luminosity (or cluster mass) versus cluster size parameter space. In the latter, strong radiative cooling reduces considerably the cluster wind mechanical energy output and affects particularly the cluster central regions, leading to frequent thermal instabilities that diminish the pressure and inhibit the exit of the reinserted matter. Instead, matter accumulates there and is expected to eventually lead to gravitational instabilities and to further stellar formation with the matter reinserted by former massive stars. The main outcome of the calculations is that the critical line is almost two orders of magnitude or more, depending on the assumed value of \( v_\infty \), lower than when only gas radiative cooling is applied. And thus, many massive clusters are predicted to enter the bimodal regime.

Key words: dust, extinction – galaxies: star clusters: general – H II regions – ISM: bubbles

1. INTRODUCTION

Data from the Spitzer and Herschel satellites have unveiled type II supernovae (SNe) as major producers of dust. Notable cases are those of the SN 1987A (see Moseley et al. 1989; Matsura et al. 2011), the Crab Nebula (Gomez et al. 2012), Cas A (Hines et al. 2004), as well as the undecided type Kepler SN (see Reynolds et al. 2007; Morgan et al. 2003), leading in all cases to dust masses, \( M_d \), of the order of several tenths to a few solar masses. The implication is that the condensation of refractory elements into dust is very efficient in the ejecta of core-collapse SNe. This result is central to explain the large amount of dust \( (\gtrsim 10^8 M_\odot) \) present in high redshift \( (z \gtrsim 6) \) galaxies (Bertoldi et al. 2003; Hines et al. 2006), as any other significant dust producer, such as the winds from low-mass evolved stars, requires an evolution time comparable to the age of the universe at that time (Morgan & Edmunds 2003). The production of dust during the explosion of type II SN has also been investigated theoretically. Todini & Ferrara (2001) and Bianchi & Schneider (2007) found that the collapse of stars with masses in the range 12–40 \( M_\odot \) with primordial metallicity, leads to the condensation of 0.08 \( M_\odot \leq M_d \leq 0.3 M_\odot \) of dust per SN. These values increase by a factor of about three if the metallicity is enhanced to solar values. Nozawa et al. (2003), considering SNe with masses up to 120 \( M_\odot \), estimated the ratio of dust mass to progenitor mass to be of the order of 0.02–0.05 and thus the calculated resultant dust masses are in excellent agreement with the values observed in young SN remnants (1987A, Cas A, the Crab nebula, and Kepler).

Here we show that the production of large quantities of dust in type II SNe also plays a major role in the hydrodynamics of the matter reinserted in young and massive superstar clusters (SSCs). In such clusters, given any reasonable IMF, one expects several tens of thousands of type II SNe spread over the first 40 Myr of evolution. The main impact of this is on the cooling at infrared frequencies expected from the dust immersed in the hot \( (\sim 10^7 K) \) thermalized ejecta, which in the adiabatic case eventually flows supersonically out of the cluster as a stationary cluster wind. The dust cooling of a hot gas was first envisaged by Ostriker & Silk (1973), who showed that the radiation from dust particles becomes larger than that generated by the gas in ionization equilibrium, including all of its possible radiative processes, at temperatures \( \sim 10^6 K \). The cooling law \( (\text{erg cm}^{-3} \text{s}^{-1}) \) then increases more than two orders of magnitude, reaching a factor of 400 above the gas cooling when this is at its minimum \( (\sim 10^7 K) \). From then onward, going to even larger temperatures, up to \( 10^9 K \), it remains about two orders of magnitude above the bremsstrahlung cooling.

Very similar results have been found by different authors for a variety of different conditions (size of grains, erosion, shock velocities, etc.) and applications (intergalactic matter in galaxy clusters, Seyfert galaxies, SNe, and their remnants). Thorough studies are those of Burke & Silk (1974), Draine (1981), Dwek & Werner (1981), Dwek (1981, 1987), Smith et al. (1996), Montier & Giard (2004), and more recently Everett & Churchwell (2010) and Guillard et al. (2009). In all of them, as in the original Ostriker & Silk (1973), dust is by far the main coolant at high temperatures. Here gas and dust cooling are added and applied to the thermalized matter reinserted by the population of massive stars in coeval young SSCs.

Section 2 shows how the expected dust sputtering time and the SN rate in massive clusters confabulate to lead to a steady state in which as dust is eroded within a cluster, it is replenished back by further SNe. This also leads to a dust-to-gas-mass
ratio $\sim 10^{-3} - 10^{-2}$. Section 3 deals with the relevance of strong radiative cooling on the matter reinserted and thermalized during the early evolutionary stages of coeval SSCs. Here we show how to find the location of the threshold line in the mechanical luminosity or cluster mass versus size of the cluster parameter space when dust radiative cooling is taken into consideration. Such a critical line separates stationary cluster winds from the bimodal cases in which strong cooling within the cluster volume leads to mass accumulation and to further star formation. This was proposed by Tenorio-Tagle et al. (2007) based on one-dimensional numerical simulations and confirmed with two-dimensional results by Wünsch et al. (2008). Our main conclusions are given in Section 4.

2. THE STATIONARY PRESENCE OF DUST WITHIN YOUNG STELLAR CLUSTERS

As pointed out by Smith et al. (1996), the inclusion of dust cooling into a time-dependent hydrodynamic evolution requires closely following how dust is eroded and how this changes the gas phase abundances. The bookkeeping has to account for the different dust constituents, the time dependent dust size distribution, and how the elemental abundances are enhanced as dust is eroded. Erosion or the sputtering of dust grains is caused mainly by the bombardment of energetic particles, such as protons, helium nuclei, and other dust grains. Electrons are usually not considered due to their low efficiency (Dwek & Arendt 1992). Here we consider the stationary situation that results from frequent SN explosions within massive SSCs. The time evolution outside the stellar cluster, within the cluster wind and its interaction with the interstellar medium (ISM) requires surely the time dependent tracking of dust sputtering and the variations of gas phase abundances. However, within the cluster volume, the average dust mass production and dust mass depletion rates must be in balance. Thus, one simply must account for the dust production rate $M_d$ as well as for the rate at which all other processes may lead to its depletion within the flow. Among these, the most obvious are sputtering and, if the dust is coupled to the gas, its exit as a constituent of the cluster wind. Such considerations lead to the relation

$$ M_d - \frac{M_d}{\tau_d} - \frac{M_d}{M_g} = 0, \quad (1) $$

where $\tau_d$ is the characteristic dust destruction time scale. The various terms in Equation (1) represent the dust mass production rate, the dust destruction rate, and the dust mass loss rate due to the outflow of the reinserted matter as a stationary cluster wind. Hereafter, we will assume that the dust mass input rate $M_g$ is in direct proportion to the gas mass input rate, $M_d = \alpha M_g$, as dust is here assumed to be injected (via SN) together with the gas (which comes from winds and SN). One can make use of Equation (1) to obtain the expected dust-to-gas-mass ratio within the considered cluster volume:

$$ Z_d = \frac{M_d}{M_g} = \frac{\alpha \tau_d M_g}{M_g} \left(1 + \frac{\tau_d M_g}{M_g}\right)^{-1}. \quad (2) $$

The factor $f_g \approx 2$ in Equation (3) takes into account the fact that the gas density within the cluster is not uniform, it drops from the center outward to reach the value $\rho_s = M_{SC}/4\pi c_s R_{SC}$ at the star cluster surface, where $c_s$ is the sound speed at the star cluster edge ($c_s \approx v_\infty/2$, $v_\infty$ is the wind terminal speed (Cantó et al. 2000; Palouš et al. 2013), and $M_{SC}$ is the mass deposition rate within the cluster volume. Note that if the stellar distribution is not homogeneous, as here assumed, then the gas density of the reinserted matter falls even more steeply (see Silich et al. 2011; Palouš et al. 2013), making the dust sputtering time even longer. Combining Equations (2) and (3), one can obtain

$$ Z_d = \frac{M_d}{M_g} = \frac{3\alpha \tau_d c_s}{f_g R_{SC}} \left(1 + \frac{3\tau_d c_s}{f_g R_{SC}}\right)^{-1}. \quad (4) $$

The mass of the reinserted gas within the star cluster radius ($R_{SC}$) is

$$ M_g = 4\pi \int_0^{R_{SC}} \rho(r)r^2 dr = \frac{f_g R_{SC} M_g}{3c_s}. \quad (3) $$

The factor $f_g \approx 2$ in Equation (3) takes into account the fact that the gas density within the cluster is not uniform, it drops from the center outward to reach the value $\rho_s = M_{SC}/4\pi c_s R_{SC}$ at the star cluster surface, where $c_s$ is the sound speed at the star cluster edge ($c_s \approx v_\infty/2$, $v_\infty$ is the wind terminal speed (Cantó et al. 2000; Palouš et al. 2013), and $M_{SC}$ is the mass deposition rate within the cluster volume. Note that if the stellar distribution is not homogeneous, as here assumed, then the gas density of the reinserted matter falls even more steeply (see Silich et al. 2011; Palouš et al. 2013), making the dust sputtering time even longer. Combining Equations (2) and (3), one can obtain

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The dust life time against sputtering at temperatures above 10⁶ K is given by Draine & Salpeter (1979):

$$ \tau_d = 10^6 \alpha n (yr) = B/\pi (s), $$

where $B = 3.156 \times 10^{13} a_\odot$ is the size of the considered dust grains in $\mu m$, and $n$ is the average nucleon number density in the gaseous phase. Substituting this relation into Equation (4) and taking into account that the average density of the reinserted matter is within a factor $f_g$ larger than at the star cluster surface ($n = f_g M_{SC}/2\pi \mu_i v_\infty R_{SC}^2$), one can obtain

$$ Z_d = \frac{M_d}{M_g} = \frac{3\pi B \mu_i R_{SC} v_\infty^4}{2 f_g^2 L_{SC}} \frac{L_{out}}{L_{SC}} \left(1 + \frac{3\pi B \mu_i R_{SC} v_\infty^4}{2 f_g^2 L_{SC}} \frac{L_{out}}{L_{SC}}\right)^{-1}, \quad (5) $$

where the ratio of the energy flux through the star cluster surface to the star cluster mechanical luminosity $L_{out}/L_{SC} = v_\infty^2/v_{A,\infty}^2$, $v_{A,\infty}^2 = 2L_{SC}/M_{SC}$ is the adiabatic wind terminal speed, $\mu_i = 14 m_H/11$ is the mean mass per nucleon, and $m_H$ is the proton mass. In the non-radiative wind model, $L_{out}$ is equal to the star cluster mechanical luminosity and $L_{out}/L_{SC} = 1$. However, in radiative winds, $L_{out} < L_{SC}$ and $v_\infty < v_{A,\infty}$ due to radiative losses of energy inside the star cluster volume.

Equation (5) shows that the dust-to-gas-mass ratio $Z_d$ must be smaller in more compact and more energetic clusters as in such clusters the average density of the reinserted matter is larger and thus the dust sputtering time is smaller. The average gas number density also increases in clusters with smaller $v_{A,\infty}$ which leads to a strong dependence of $Z_d$ on the adiabatic wind terminal speed. Note that the value of $Z_d$ can never exceed that in the injected matter and it sets the upper limit for the dust over gas mass ratio inside the cluster: $Z_d < \alpha$. Figure 1 presents the expected dust-to-gas-mass ratio in clusters with different sizes, mechanical luminosities, and adiabatic wind terminal speeds containing dust grains of different sizes. Taking a conservative point of view, it was assumed that stellar winds and SNe contribute similar amounts of gas (Leitherer et al. 1999) and thus the dust-to-gas-mass ratio in the injected matter is two times smaller than the lowest value obtained by Nozawa et al. (2003) for SNe ejecta: $\alpha = 0.01$. $L_{out}/L_{SC}$ was set to values consistent with those found at the critical line that separates stationary and thermally unstable solutions: 0.69 for $v_{A,\infty} = 1000$ km s⁻¹, 0.77 for $v_{A,\infty} = 1500$ km s⁻¹, and 0.82 for $v_{A,\infty} = 2000$ km s⁻¹, respectively.

Note that only in the most energetic and compact clusters considered here does the value of $Z_d$ fall below $10^{-3}$ (dashed line in panel (a)) while in other clusters, either with different mechanical luminosities (panel (a)) or different wind terminal...
Figure 1. Expected dust-to-gas-mass ratio inside young stellar clusters. Panel (a) presents the dust-to-gas-mass ratio, $Z_d$, calculated by means of Equation (5) for clusters with different mechanical luminosities ($L_{SC} = 10^{40}$ erg s$^{-1}$, $L_{SC} = 10^{41}$ erg s$^{-1}$, and $L_{SC} = 10^{40}$ erg s$^{-1}$—solid, dashed, and dotted lines, respectively) as a function of the star cluster radius, when the assumed size of the dust grains is $a = 0.1 \mu m$ and the adiabatic wind terminal speed is $v_{A\infty} = 1000$ km s$^{-1}$. Panel (b) displays the same ratio for clusters with a mechanical luminosity $L_{SC} = 10^{40}$ erg s$^{-1}$ and different adiabatic wind terminal speeds: $v_{A\infty} = 1000$ km s$^{-1}$, $v_{A\infty} = 1500$ km s$^{-1}$, and $v_{A\infty} = 2000$ km s$^{-1}$, solid, dotted, and dashed lines, respectively. Panel (c) shows $Z_d$ in clusters with $L_{SC} = 10^{40}$ erg s$^{-1}$ and $v_{A\infty} = 1000$ km s$^{-1}$ when dust grains have different radii: $a = 0.1 \mu m$, $a = 0.5 \mu m$, and $a = 0.02 \mu m$: solid, dashed, and dotted lines, respectively.

speeds (panel (b)), the dust-to-gas-mass ratio always falls in the range $10^{-3} \lesssim Z_d \lesssim 10^{-5}$ unless the size of the dust grains is very small (panel (c)). The implication is that within a star cluster volume, as dust grains are sputtered they are replenished back by further SNe, causing a stationary presence of dust. Such a condition points to the importance of dust in the thermodynamics of the matter reinserted within SSCs.

2.1. The Dust Cooling Law

Following Dwek & Werner (1981), we have calculated the cooling function due to gas-grain collisions for a plasma with a normal chemical composition (one He atom per every ten H atoms) as

$$\Lambda_d = \frac{n_d}{n_e n_H} H_{coll} = \frac{1.4 m_H Z_d}{\langle m_d \rangle} \left( \frac{23}{\pi m_e} \right)^{1/2} \pi a^2 (kT)^{3/2} \times \left[ h_e + \frac{11}{23} \left( \frac{m_e}{m_H} \right)^{1/2} h_n \right],$$

where $n_d$, $n_e$, and $n_H$ are the dust, electron, and hydrogen particle number density, and $H_{coll}$ is the heating rate of a single grain due to collisions of incident gas particles. The functions $h_e$ and $h_H$ are the effective grain heating efficiencies due to incident
electrons and nuclei, respectively:

\[ h_e = 1 - \int_0^\infty \frac{(z + x_e)(z + x_e)^{3/2}}{(z + x_e)^3} \, dz, \]

\[ h_n = 1 - (1 + E_H/kT) \exp(-E_H/kT), \]

where \( m_H \) is the proton mass, \( m_d = 4/3\pi \rho_d a^3 \) is the mass of the dust grains, \( x_e = E_e/kT \), \( E_e = 23a^{2/3} \) (\( \mu_m \)) keV, and \( E_H = 133a (\mu_m) \) keV. We neglected the dust grains’ charge (Smith et al. 1996) and assumed that all of them have the same size \( a \) and density \( \rho_d = 3 \) g cm\(^{-3} \).

Figure 2 shows the cooling curve obtained for dust grains with \( a = 0.1 \) \( \mu_m \) and different \( Z_e \), compared to the gas cooling function. The curve for \( Z_d = 6 \times 10^{-3} \) reproduces that of Dwek & Werner (1981, their Figure 2).

3. STRONG RADIATIVE COOLING AND THE LOCATION OF THE THRESHOLD LINE

As shown in a recent series of papers (Silich et al. 2004; Tenorio-Tagle et al. 2005a, 2007; Wünsch et al. 2008, 2011), the effects of gas radiative cooling on the hydrodynamics of the matter reinserted by winds and SN explosions within homogeneous, young, massive and compact stellar clusters may lead to a bimodal solution, instead of the powerful stationary regime (cases above the threshold line), the main difference is that strong radiative cooling becomes important, particularly within the cluster’s densest central regions, and this causes zones within the flow to frequently become thermally unstable. The instabilities cause a sudden loss of pressure and this inhibits the outward acceleration required to form part of the cluster wind. Instead, the unstable parcels of gas begin to accumulate while condensing under the action of the surrounding hot matter, in search of a rapid re-establishment of an even pressure. That leads eventually to a gravitational instability and thus to an extreme positive star formation feedback condition, in which further generations of stars form within the cluster volume with the matter reinserted by massive stars (Tenorio-Tagle et al. 2005a, 2005b).

As we have shown (Tenorio-Tagle et al. 2007; Wünsch et al. 2008), only clusters located above the threshold line in the mechanical luminosity (or cluster mass) versus size diagram are able to undergo the bimodal solution. In all such clusters with a homogeneous stellar density distribution, the frequent and recurrent thermal instabilities promote the exit of the stagnation radius out of the cluster center and make it approach the cluster boundary, and the more this occurs, the further above the threshold line the considered clusters are. Matter reinserted in the volume between the stagnation radius and the cluster edge still manages to accelerate and reach the sonic point right at the cluster edge and thus composes a wind.

Here we search for the location of the threshold line when cooling by dust is also included following the procedure given by Tenorio-Tagle et al. (2007). The integration of the hydrodynamic equations for the flow demands knowledge of the temperature at the stagnation point, \( T_0 \), which may be found by iteration until the sonic point is accommodated at the cluster edge.

In this way, a unique stagnation temperature is selected from the branch of possible temperatures, and once the selected temperature corresponds to the maximum pressure, the critical energy has been reached. We can thus select the cluster parameters \( (R_{SC}, V_{\infty}, L_{SC}) \) as well as the dust parameters \( (a \text{ and } \rho_d) \) and through Equation (5) find \( Z_d \). This allows one to calculate the dust cooling curve and with this, and by iteration, find the largest mechanical energy for which a stationary wind results with its stagnation point at the cluster center and that reaches its local sound speed at the cluster surface.

Figure 3 shows the location of the threshold line derived when using only gas cooling from a gas in collisional ionization equilibrium (see Silich et al. 2004; Tenorio-Tagle et al. 2007) compared to the critical line when one adds gas and dust cooling. Dust cooling lowers the threshold cluster mechanical luminosity (or cluster mass) by about 2 dex or more, depending on the assumed value of \( V_{\infty} \). Thus, many massive (\( M_{SC} \gtrsim 10^5 M_\odot \)) clusters that appear to be quasi-adiabatic when one considered only gas cooling, are now well above the threshold line, and thus in the bimodal regime. The calculations show that at the critical line, the fraction of the injected energy that clusters return to the ISM \( L_{rad}/L_{SC} \approx 0.69 \), and as was shown by Tenorio-Tagle et al. (2007), this decreases monotonically as one selects more massive clusters with a larger excess energy above the critical value \( (L_{SC}/L_{crit}; \text{see Figure } 5 \text{ of Tenorio-Tagle et al. 2007}) \). Thus, radiative cooling may strongly deplete the mechanical energy output from massive clusters and thus reduce their negative star formation feedback into the ISM.

Figure 4 displays the run of velocity, as well as temperature and density, for clusters with 1 pc and 10 pc radius and a luminosity \( L_{SC} = 7.13 \times 10^{38} \text{ erg s}^{-1} \) and \( L_{SC} = 7.13 \times 10^{39} \text{ erg s}^{-1} \).
Figure 3. Threshold mechanical luminosity. Panels (a) and (b) present $L_{\text{crit}}$ calculated for $V_{\infty} = 1000$ and 2000 km s$^{-1}$ under the assumption of pure gas cooling (solid lines) and when gas and dust cooling are added (dashed lines). In all cases, dust grains were assumed to have a radius $a = 0.1 \mu$m.

Figure 4. Impact of dust radiative cooling on the distribution of the hydrodynamical variables. Panels (a), (b), and (c) present the wind velocity, temperature, and density, respectively. The thin and thick lines display the results of the calculations for clusters with $R_{SC} = 1$ pc and $R_{SC} = 10$ pc. The dashed and solid lines correspond to models with and without dust cooling, respectively. The same adiabatic wind terminal speed and grain sizes were used in all calculations: $V_{\infty} = 1000$ km s$^{-1}$ and $a = 0.1 \mu$m.
respectively. Such values place them at the critical line when dust and gas cooling are considered. The figure compares the run of all of these variables with those derived for the quasi-adiabatic solution when only gas radiative cooling is considered. The large central temperature depressions at the critical line and the slow acceleration of the reinserted matter within the cluster are indicative of the last stationary solution found before crossing the critical line.

The presence of dust in the thermalized plasma within young SSCs provides a natural explanation for the observational and theoretical studies that have derived a strongly reduced mechanical energy output from some of the massive clusters in the galaxy M82 in order to account for the size of the compact 
H\textsc{ii} regions that surround them (see Smith et al. 2006; Silich et al. 2007, 2009). Further evidence for the bimodal solution and the positive star formation feedback may come from the interpretation of the abundance variations from star to star in massive globular clusters (GC), such as \omega\ Cen in the Milky Way where different generations of stars are enriched by different contributors, and among these by core-collapse SNe (Gratton et al. 2004) or from observations of the most massive GCs in M31 where the run of $\alpha$ to Fe-peak elements is consistent with a primordial enrichment from stars with masses larger than 10 $M_\odot$ (Meylan et al. 2001). The super-solar $\alpha$ to Fe element ratios indicating the fast gas enrichment by Type II SNe were also detected by Larsen et al. (2006), who have obtained the near-IR $H$- and $K$-band spectra and provided a detailed abundance analysis of a young massive cluster in the nearby spiral galaxy NGC 6946. Also, the presence of the hot dust component ($\sim$800 K) is required in order to fit the UV to near IR spectral energy distribution of SSCs 1 and 2 in the low metallicity galaxy ($Z = 1/40 Z_\odot$) SBS 0335-052 (see Figure 8 of Reines et al. 2008).

4. CONCLUSIONS

Observational and theoretical evidence points to an efficient condensation of refractory elements into dust in the ejecta of core-collapse SN. The several thousands of type II SNe expected in young and massive SSCs has led us to postulate a continuous presence of dust in the SSCs volume and conclude that the likely range of dust-to-gas-mass ratios is $Z_\text{d} \sim 10^{-2}$ to $10^{-3}$, which has allowed us to calculate the dust cooling law within young and massive SSCs. Dust cooling effectively lowers the location of the critical line that separates clusters with stationary outflows from those evolving in the bimodal regime. The new location implies that young, massive and compact SSCs with masses $M_{\text{sc}} > 10^5 M_\odot$ experience the bimodal solution.

The implication of assuming gas and dust cooling is thus that for young, massive and compact stellar clusters only a fraction of their mechanical luminosity, as inferred from synthesis models (as in SB99), impacts the surrounding ISM. Massive, compact and young clusters thus inject into the ISM only a fraction of their reinserted matter and of their processed metals and with a velocity that is more strongly diminished the further above the critical line the considered clusters are. Meanwhile, the matter reinserted within the thermally unstable volume is continuously reprocessed into dense compact clouds compressed by the surrounding hot plasma and photoionized by the parental cluster Lyman continuum. Mass accumulation would lead to surpassing the Jeans instability limit and to an extreme mode of positive star formation feedback within the cluster volume, where the matter reinserted by massive stars leads to new stellar generations.

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REFERENCES

Bertoldi, F., Cox, P., Neri, R., et al. 2003, A&A, 409, L47
Bianchi, S., & Schneider, R. 2007, MNRAS, 378, 973
Burke, J. R., & Silk, J. 1974, ApJ, 190, 199
Cantó, J., Raga, A. C., & Rodríguez, L. F. 2000, ApJ, 536, 896
Chevalier, R. A., & Clegg, A. W. 1985, Natuir., 317, 44
Draine, B. T. 1981, ApJ, 245, 880
Draine, B. T., & Salpeter, E. E. 1979, ApJ, 231, 77
Dwek, E. 1981, ApJ, 247, 614
Dwek, E. 1987, ApJ, 322, 844
Dwek, E., & Arendt, R. G. 1992, ARA&A, 30, 11
Dwek, E., & Werner, M. W. 1981, ApJ, 248, 138
Everett, J. E., & Churchwell, E. 2010, ApJ, 713, 592
Gomez, H. L., Krause, O., Barlow, M. J., et al. 2012, ApJ, 760, 96
Gratton, R., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385
Guillard, P., Boulanger, F., Pineau Des Forêts, G., & Appleton, P. N. 2009, A&A, 502, 515
Hines, D. C., Krause, O., Rieke, G. H., et al. 2006, ApJL, 641, L85
Hines, D. C., Rieke, G. H., Gordon, K. D., et al. 2004, ApJS, 154, 290
Larsen, S. S., Origlia, L., Brodie, J. P., & Gallagher, J. S. 2006, MNRAS, 368, L10
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
Matsusara, M., Dwek, E., Meixner, M., et al. 2011, Sci, 333, 1258
Meylan, G., Sarajedini, A., Jablonka, P., et al. 2001, AJ, 122, 830
Montier, L. A., & Giard, M. 2004, A&A, 417, 401
Morgan, H. L., Dunne, L., Eales, S. A., Ivison, R. J., & Edmunds, M. G. 2003, ApJL, 597, L33
Morgan, H. L., & Edmunds, M. G. 2003, MNRAS, 343, 427
Moseley, S. H., Dwek, E., Glaccum, W., Graham, J. R., & Loewenstein, R. F. 1989, Natur., 340, 697
Nozawa, T., Kozasa, T., Umeda, H., Maeda, K., & Nomoto, K. 2003, ApJ, 598, 785
Ostriker, J., & Silk, J. 1973, ApJL, 184, L113
Palouš, J., Wünsch, R., Martínez-González, S., et al. 2013, ApJ, 772, 128
Reines, A. E., Johnson, K. E., & Hunt, L. K. 2008, AJ, 136, 1415
Reynolds, S. P., Borkowski, K. J., Hwang, U., et al. 2007, ApJL, 668, L135
Silich, S., Bisnovatyi-Kogan, G., Tenorio-Tagle, G., & Martínez-González, S. 2011, ApJ, 743, 120
Silich, S., Tenorio-Tagle, G., & Muñoz-Tuñón, C. 2007, ApJ, 669, 952
Silich, S., Tenorio-Tagle, G., & Rodríguez-González, A. 2004, ApJ, 610, 226
Silich, S., Tenorio-Tagle, G., Torres-Campos, A., et al. 2009, ApJ, 700, 931
Smith, L. J., Westmoquette, M. S., Gallagher, J. S., et al. 2006, MNRAS, 370, 513
Smith, R. K., Krzewska, L. G., Cox, D. P., Edgar, R. J., & Miller, W. W. 1996, ApJ, 473, 864
Tenorio-Tagle, G., Silich, S., Rodríguez-González, A., & Muñoz-Tuñón, C. 2005a, ApJL, 628, L13
Tenorio-Tagle, G., Silich, S., Rodríguez-González, A., & Muñoz-Tuñón, C. 2005b, ApJ, 620, 217
Tenorio-Tagle, G., Wünsch, R., Silich, S., & Palouš, J. 2007, ApJ, 658, 1196
Todini, P., & Ferrara, A. 2001, MNRAS, 325, 726
Wünsch, R., Silich, S., Palouš, J., Tenorio-Tagle, G., & Muñoz-Tuñón, C. 2011, ApJ, 740, 75
Wünsch, R., Tenorio-Tagle, G., Palouš, J., & Silich, S. 2008, ApJ, 683, 683