



Interstellar Dust as an Active Regulator of Star Formation: A Comparative Radiative, Chemical, and Magnetohydrodynamic Framework Across Spiral, Elliptical, and Irregular Galaxies

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ABSTRACT

Interstellar dust plays a fundamental role in regulating the physical and chemical evolution of the interstellar medium (ISM) and star-forming regions across different galaxy types. This study presents a physical framework describing how dust grains influence star formation through a coupled sequence of radiative, chemical, and magnetohydrodynamic processes. Dust grains efficiently absorb ultraviolet and optical radiation and re-emit the energy in the infrared, modifying the thermal balance of the surrounding gas. Dust surfaces also facilitate recombination by capturing free electrons and ions, decreasing the ionization fraction of the medium. This reduction in ionization weakens the coupling between neutral gas and magnetic fields, enhancing ambipolar diffusion and reducing magnetic support against gravitational collapse. The associated decrease in gas temperature lowers the Jeans mass, enabling instability at smaller mass scales,

while the mass-to-magnetic-flux ratio approaches or exceeds the critical threshold marking the transition to gravitationally dominated collapse. Comparative analysis of infrared emission from three galaxies of different morphological type — the spiral galaxy NGC 628, the elliptical galaxy NGC 1399, and the irregular galaxy NGC 1427A — supports this sequence, showing that dust-rich systems display structured emission consistent with active star formation, whereas the dust-poor elliptical galaxy shows diffuse emission consistent with suppressed star formation. This framework demonstrates that interstellar dust acts as an active regulator of star formation rather than a passive component of the interstellar medium.

INTRODUCTION

Interstellar dust is a minor yet dynamically crucial component of the interstellar medium (ISM), significantly influencing the thermal, chemical, and dynamical evolution of galaxies¹². Although dust constitutes only a



small fraction of the total baryonic mass, it plays a key role in radiative transfer, gas cooling, and the formation of molecular clouds, which serve as the primary sites of star formation¹.

Observations across different galaxy types, including spiral, elliptical, and irregular systems, reveal that dust distribution strongly correlates with star formation activity and gas-phase physical conditions². Infrared observations demonstrate that dust reprocesses absorbed ultraviolet and optical radiation into thermal emission, making it an essential tracer of obscured star-forming regions. This study focuses on three representative systems — the spiral galaxy NGC 628, the elliptical galaxy NGC 1399, and the irregular galaxy NGC 1427A — to investigate how dust properties vary across different galactic environments.

Beyond its radiative role, interstellar dust significantly affects the microphysics of the ISM. Dust grains interact with the surrounding plasma by capturing free electrons and ions, modifying the ionization balance of the medium³⁴. This process

directly influences the coupling between neutral gas and magnetic fields, a fundamental factor in magnetohydrodynamic evolution. In regions of low ionization, the decoupling of neutral and charged components leads to enhanced ambipolar diffusion, allowing neutrals to drift relative to magnetic field lines⁵⁶.

The interplay between dust, ionization fraction, and magnetic coupling has important consequences for gravitational stability. Reduced ionization weakens magnetic support, while efficient radiative cooling lowers the thermal pressure of the gas⁷⁸. As a result, the Jeans mass

of the Interstellar Medium (Cambridge: Cambridge University Press, 2005), <https://doi.org/10.1017/CBO9780511819056>.

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⁵L. Mestel and L. Spitzer, "Star Formation in Magnetic Dust Clouds," *Monthly Notices of the Royal Astronomical Society* 116, no. 5 (1956): 503–514,

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⁶Richard M. Crutcher, "Magnetic Fields in Molecular Clouds," *Annual Review of Astronomy and Astrophysics* 50 (2012): 29–63, <https://doi.org/10.1146/annurev-astro-081811-125514>.

⁷Christopher F. McKee and Eve C. Ostriker, "Theory of Star Formation," *Annual Review of Astronomy and Astrophysics* 45 (2007): 565–687, <https://doi.org/10.1146/annurev.astro.45.051806.110602>.

⁸Mark R. Krumholz, "The Big Problems in Star Formation," *Physics Reports* 539 (2014): 49–134, <https://doi.org/10.1016/j.physrep.2014.02.001>.

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²B.T. Draine, "Interstellar Dust Grains," *Annual Review of Astronomy and Astrophysics* 41 (2003): 241–289, <https://doi.org/10.1146/annurev.astro.41.011802.094840>.

³A.G.G.M. Tielens, *The Physics and Chemistry*



decreases, enabling gravitational collapse at smaller spatial scales. In addition, the mass-to-magnetic-flux ratio may approach or exceed the critical threshold required for collapse, marking the transition from magnetically supported clouds to gravitationally dominated structures⁹.

This work proposes a unified physical framework linking dust radiative processing, ionization regulation, ambipolar diffusion, and magnetic decoupling to the onset of star formation. By combining infrared observations with theoretical considerations, this study aims to demonstrate that interstellar dust is not merely a passive tracer of galactic structure but an active regulator of star-forming processes across different galaxy environments.

RESULTS

A comparative analysis of infrared dust emission and structural properties was performed across three galaxies: NGC 628, NGC 1399, and NGC 1427A.

The results are based on WISE W3 (12 μm) infrared observations combined with isocontour mapping of emission intensity,

allowing the spatial distribution of interstellar dust to be examined in detail¹⁰.

NGC 628: Spiral Galaxy

The WISE W3 map of NGC 628 reveals a highly structured dust distribution concentrated along well-defined spiral arms. The isocontour analysis shows strong intensity gradients tracing these arms, indicating dense dust accumulation regions. These structures are consistent with active star-forming regions, where dust-rich molecular clouds are concentrated. The spatial correlation between spiral morphology and infrared emission suggests efficient coupling between gas dynamics and dust-driven radiative processes.

NGC 1399: Elliptical Galaxy

In contrast, NGC 1399 exhibits a relatively smooth and diffuse infrared emission profile. The isocontour levels show weak spatial variation, indicating a low abundance of interstellar dust. The absence of strong dust structures is consistent with the suppressed star formation activity typical of elliptical galaxies. The infrared emission is dominated by evolved stellar populations rather than dust-heated star-forming regions.

⁹Richard M. Crutcher, "Magnetic Fields in Molecular Clouds," *Annual Review of Astronomy and Astrophysics* 50 (2012): 29–63, <https://doi.org/10.1146/annurev-astro-081811-125514>.

¹⁰E.L. Wright et al., "The Wide-field Infrared Survey Explorer (WISE)," *The Astronomical Journal* 140, no. 6 (2010): 1868–1881, <https://doi.org/10.1088/0004-6256/140/6/1868>.



NGC 1427A: Irregular Galaxy

NGC 1427A displays a highly irregular and clumpy infrared morphology. The isocontour maps reveal localized high-intensity regions embedded within a diffuse background, indicating spatially inhomogeneous dust distribution.

DISCUSSION

The infrared observations of NGC 628, NGC 1399, and NGC 1427A suggest that interstellar dust is not merely a passive tracer of galactic structure but an active regulator of star formation and the physical evolution of the interstellar medium. The observed differences in dust morphology among spiral, elliptical, and irregular galaxies can be interpreted through a sequence of interconnected physical processes.

1. Absorption of Ultraviolet Radiation

Interstellar dust grains efficiently absorb ultraviolet and optical photons because grain sizes are comparable to these wavelengths^{11,12}. This attenuation of radiation is commonly described by the extinction

¹¹B.T. Draine, "Interstellar Dust Grains," Annual Review of Astronomy and Astrophysics 41 (2003): 241–289, <https://doi.org/10.1146/annurev.astro.41.011802.094840>.

¹²A.G.G.M. Tielens, The Physics and Chemistry of the Interstellar Medium (Cambridge: Cambridge University Press, 2005), <https://doi.org/10.1017/CBO9780511819056>.

relation $I = I_0 e^{-\tau_\lambda}$, where I is the transmitted intensity and τ_λ is the optical depth. Dust-rich systems such as NGC 628 and NGC 1427A therefore exhibit significant extinction and obscured star-forming regions, whereas the dust-poor elliptical galaxy NGC 1399 experiences much weaker attenuation.

2. Infrared Re-emission and Dust Heating

The absorbed energy is re-emitted thermally in the infrared. The thermal emission of dust can be approximated as $L_v \propto B_v(T_d) \cdot \kappa_v \cdot M_d$, where $B_v(T_d)$ is the Planck function, T_d is the dust temperature, κ_v is the dust opacity, and M_d is the dust mass

^{13,14}. This process explains why the WISE W3 and W4 bands trace dust-rich regions in NGC 628 and NGC 1427A, while NGC 1399 exhibits comparatively weak infrared emission.

3. Dust and the Ionization Fraction

Dust grains capture free electrons and ions ($e^- + \text{dust} \rightarrow \text{dust}^-$), thereby reducing the ionization fraction $x_e = n_e/n_H$, where

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n_e is the electron number density and n_H is the hydrogen number density¹⁵. Cosmic rays continuously ionize molecular gas; however, dust grains facilitate recombination and lower x_e . Consequently, dust-rich galaxies are expected to exhibit lower ionization fractions within dense molecular regions^{16,17}.

4. Enhancement of Ambipolar Diffusion

The decrease in ionization weakens the coupling between the neutral gas and magnetic fields^{18,19}. The characteristic ambipolar diffusivity is $\eta_{AD} = B^2/(4\pi\gamma\rho_i\rho_n)$, where B is the magnetic field strength, ρ_i is the ion density, ρ_n is the neutral density, and γ is the ion-neutral coupling coefficient. As the ion density decreases, η_{AD} increases, allowing neutral gas to drift relative to magnetic field

lines. This effect is expected to be strongest in the dust-rich spiral and irregular galaxies²⁰.

5. Reduction of the Jeans Mass

Dust cooling lowers the gas temperature and therefore decreases the Jeans mass, $M_J = (5k_B T/G\mu m_H)^{3/2} \cdot (3/4\pi\rho)^{1/2}$. A lower temperature reduces M_J , enabling gravitational collapse at smaller mass scales. This mechanism naturally favours fragmentation and star formation in dust-rich environments

^{21,22}.

6. Critical Mass-to-Flux Ratio

Magnetic support against collapse is quantified through the normalized mass-to-flux ratio, $\mu = (M/\Phi)/(M/\Phi)_{crit}$, where $(M/\Phi)_{crit} = 1/(2\pi\sqrt{G})$. For $\mu < 1$, clouds are magnetically subcritical and resist collapse, whereas $\mu > 1$ indicates gravitationally unstable clouds. Enhanced ambipolar

¹⁵A.G.G.M. Tielens, *The Physics and Chemistry of the Interstellar Medium* (Cambridge: Cambridge University Press, 2005), <https://doi.org/10.1017/CBO9780511819056>.

¹⁶N. Indriolo and B.J. McCall, "Cosmic-Ray Ionization in the Diffuse Interstellar Medium," *Astrophysical Journal* 745 (2012): 91, <https://doi.org/10.1088/0004-637X/745/1/91>.

¹⁷A.G.G.M. Tielens, *The Physics and Chemistry of the Interstellar Medium* (Cambridge: Cambridge University Press, 2005), <https://doi.org/10.1017/CBO9780511819056>.

¹⁸L. Mestel and L. Spitzer, "Star Formation in Magnetic Dust Clouds," *Monthly Notices of the Royal Astronomical Society* 116, no. 5 (1956): 503–514, <https://doi.org/10.1093/mnras/116.5.503>.

¹⁹Richard M. Crutcher, "Magnetic Fields in Molecular Clouds," *Annual Review of Astronomy and Astrophysics* 50 (2012): 29–63, <https://doi.org/10.1146/annurev-astro-081811-125514>.

²⁰Richard M. Crutcher, "Magnetic Fields in Molecular Clouds," *Annual Review of Astronomy and Astrophysics* 50 (2012): 29–63, <https://doi.org/10.1146/annurev-astro-081811-125514>.

²¹Christopher F. McKee and Eve C. Ostriker, "Theory of Star Formation," *Annual Review of Astronomy and Astrophysics* 45 (2007): 565–687, <https://doi.org/10.1146/annurev.astro.45.051806.110602>.

²²Mark R. Krumholz, "The Big Problems in Star Formation," *Physics Reports* 539 (2014): 49–134, <https://doi.org/10.1016/j.physrep.2014.02.001>.



diffusion in dust-rich environments allows molecular clouds to approach or exceed this critical threshold^{23,24}.

7. Initiation of Star Formation

Once magnetic support weakens and the Jeans criterion is satisfied, gravitational collapse begins. Molecular clouds fragment into dense cores that eventually form protostars^{25,26}. The infrared morphology of NGC 628 and NGC 1427A is consistent with this sequence, exhibiting abundant dust and localized star-forming regions. Conversely, NGC 1399 contains little dust, weak infrared emission, and limited evidence for ongoing star formation.

Dust, Cosmic Rays, and Synchrotron Processes

Dust grains absorb ultraviolet and optical radiation and subsequently re-emit the

absorbed energy in the infrared. Cosmic rays contribute to the ionization of molecular gas, while synchrotron radiation arises from relativistic electrons spiralling around magnetic field lines²⁷. Although dust does not strongly absorb synchrotron radiation directly, dust-driven modifications of the ionization fraction and magnetic field structure indirectly influence the conditions under which synchrotron emission is produced²⁸.

Overall Evolutionary Sequence and Conclusions

The observations and theoretical considerations support the following sequence: dust absorbs ultraviolet radiation, re-emits it in the infrared, the ionization fraction x_e decreases, ambipolar diffusivity η_{AD} increases, the Jeans mass M_J decreases, the mass-to-flux ratio μ increases, and gravitational collapse leads to star formation.

This framework demonstrates that interstellar dust acts as a fundamental regulator of radiative transfer, ionization balance, magnetic coupling, and ultimately

²³Richard M. Crutcher, "Magnetic Fields in Molecular Clouds," *Annual Review of Astronomy and Astrophysics* 50 (2012): 29–63, <https://doi.org/10.1146/annurev-astro-081811-125514>.

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²⁸Richard M. Crutcher, "Magnetic Fields in Molecular Clouds," *Annual Review of Astronomy and Astrophysics* 50 (2012): 29–63, <https://doi.org/10.1146/annurev-astro-081811-125514>.



star formation across different galactic environments^{29,30,31}. Future work combining higher-resolution infrared and polarimetric observations would allow more direct tests of the ambipolar diffusion and mass-to-flux ratio predictions outlined here.

MATERIALS AND METHODS

This study combines infrared observational data with a comparative physical analysis of interstellar dust properties across different galaxy types. Three representative galaxies were selected — the spiral galaxy NGC 628, the elliptical galaxy NGC 1399, and the irregular galaxy NGC 1427A — to represent distinct morphological classes and environmental conditions, enabling a comparative study of dust-related processes in diverse galactic contexts.

Infrared Data Acquisition

Infrared observations were obtained from the Wide-field Infrared Survey Explorer

(WISE) mission³². The W3 (12 μ m) band was primarily used owing to its sensitivity to polycyclic aromatic hydrocarbons (PAHs) and warm interstellar dust emission. In some cases, the W4 (22 μ m) band was additionally used to trace hotter dust components associated with active star-forming regions³³. The infrared data provide a direct tracer of dust distribution, allowing the identification of dust-rich regions that are not visible at optical wavelengths owing to extinction.

Image Processing and Isocontour Mapping

To quantify the spatial distribution of dust emission, infrared images were processed to generate isocontour maps. These contours represent constant intensity levels in the infrared emission, highlighting structural variations in dust density across each galaxy. The contouring procedure was applied uniformly across all three galaxies to ensure consistent comparison. The resulting maps were used to identify regions of enhanced dust concentration, which are associated with molecular clouds and potential star-forming regions.

²⁹B.T. Draine, "Interstellar Dust Grains," Annual Review of Astronomy and Astrophysics 41 (2003): 241–289, <https://doi.org/10.1146/annurev.astro.41.011802.094840>.

³⁰B. Draine, Physics of the Interstellar and Intergalactic Medium (Princeton: Princeton University Press, 2010), <https://doi.org/10.1515/9781400839087>.

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³³E.L. Wright et al., "The Wide-field Infrared Survey Explorer (WISE)," The Astronomical Journal 140, no. 6 (2010): 1868–1881, <https://doi.org/10.1088/0004-6256/140/6/1868>.



Comparative Morphological Analysis

Each galaxy was analysed according to its morphological type. NGC 628, a spiral galaxy, is characterised by well-defined spiral arms and high dust content concentrated along the disk structure. NGC 1399, an elliptical galaxy, exhibits low dust content and a relatively uniform infrared background, indicating suppressed star formation activity. NGC 1427A, an irregular galaxy, displays asymmetric and clumpy dust distribution, reflecting ongoing and spatially inhomogeneous star formation.

Physical Interpretation Framework

The observational results were interpreted using a theoretical framework based on interstellar medium physics. In this framework, dust grains influence the ionization fraction of the gas by capturing free electrons and ions, thereby modifying the coupling between neutral gas and magnetic fields^{34,35}. This coupling is quantified through the ionization fraction $x_e = n_e/n_H$, which directly affects ambipolar diffusion efficiency³⁶. Changes in ionization

state influence the magnetic flux transport, thermal balance, and gravitational stability of molecular clouds.

Star Formation Criteria

The onset of gravitational collapse was evaluated using two key physical criteria: the Jeans instability condition and the mass-to-magnetic-flux ratio. The Jeans mass depends on gas temperature and density, while the mass-to-flux ratio determines whether magnetic support can prevent collapse^{37,38}. Regions where radiative cooling by dust reduces the gas temperature and where ionization levels are sufficiently low are considered favourable for star formation.

³⁴A.G.G.M. Tielens, *The Physics and Chemistry of the Interstellar Medium* (Cambridge: Cambridge University Press, 2005), <https://doi.org/10.1017/CBO9780511819056>.

³⁵B. Draine, *Physics of the Interstellar and Intergalactic Medium* (Princeton: Princeton University Press, 2010), <https://doi.org/10.1515/9781400839087>.

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FIGURES AND FIGURE TITLES/CAPTIONS

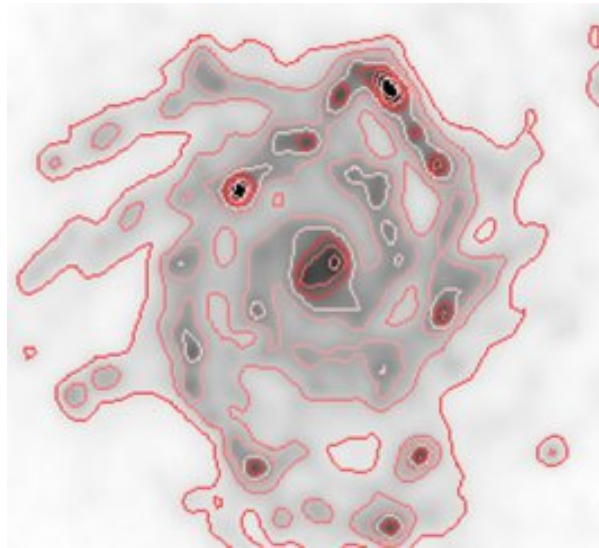


Figure 1. Infrared isocontour map of NGC 628 (spiral galaxy).

WISE W3 (12 μm) isocontour map showing ordered, disk-aligned dust distribution with strong structural coherence along the spiral arms. $n = 1$ galaxy.

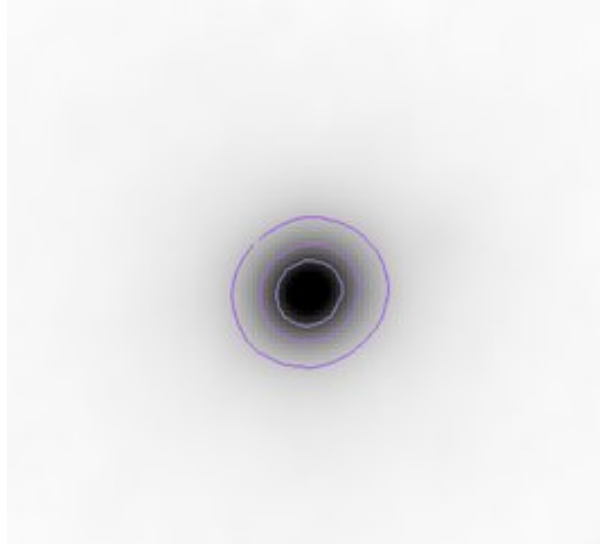


Figure 2. Infrared isocontour map of NGC 1399 (elliptical galaxy).

WISE W3 (12 μ m) isocontour map showing weak and diffuse dust emission with minimal spatial structure, consistent with low dust content. n = 1 galaxy.

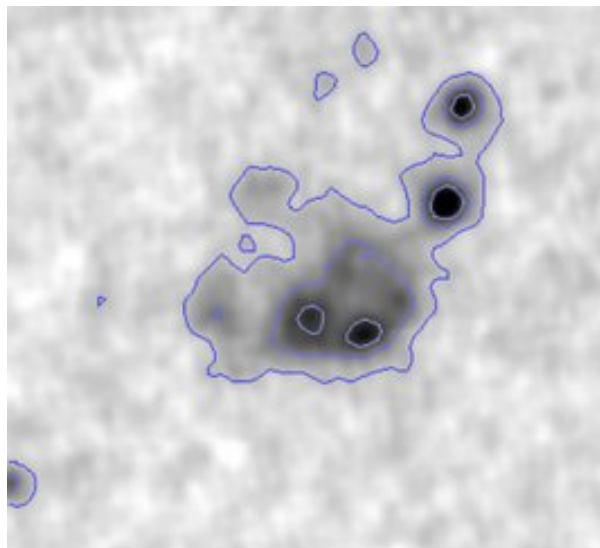


Figure 3. Infrared isocontour map of NGC 1427A (irregular galaxy).

WISE W3 (12 μ m) isocontour map showing fragmented and clumpy dust distribution with localized emission peaks, indicating spatially inhomogeneous star formation. n = 1 galaxy.

TABLES WITH TITLES/CAPTIONS



Table 1. Comparative dust and infrared properties of the three sample galaxies.

Galaxy	Morphological Type	Dust Distribution	Infrared Emission (WISE W3)	Inferred Star Formation Activity
NGC 628	Spiral	Ordered, disk-aligned, concentrated along spiral arms	Strong, highly structured	Active
NGC 1399	Elliptical	Diffuse, low abundance	Weak, spatially uniform	Suppressed
NGC 1427A	Irregular	Clumpy, asymmetric	Localized high-intensity peaks	Ongoing, spatially inhomogeneous

Caption: Summary of morphological classification, dust distribution, WISE W3 infrared emission characteristics, and inferred star formation activity for NGC 628, NGC 1399, and NGC 1427A, based on isocontour mapping described in Materials and Methods.

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