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A New Computational Method for Dust and Gas Dynamics in Protoplanetary Discs

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Abstract

The simultaneous evolution of dust and gas in protoplanetary discs regulates essential events in planet formation, such as dust accumulation, migration, and the initiation of gravitational instabilities. Nevertheless, precisely modelling this interaction continues to provide a significant computing problem owing to the extensive variety of spatial and temporal scales involved. In this study, we introduce an innovative computational framework for simulating dust-gas dynamics in protoplanetary discs, integrating a two-fluid hydrodynamical formulation with an adaptive, high-resolution numerical method. Our technique takes into account both aerodynamic drag and turbulent diffusion, and it keeps the gas and dust momentum equations consistent with one other. Benchmark experiments against analytical solutions and existing numerical models show that our method works better and is more stable over a wide range of Stokes values. We utilise this paradigm to investigate dust concentration and entrapment in pressure bumps, uncovering novel insights into the conditions conducive to planetesimal formation. This computational method is a strong and useful way to study how dust and gas interact in protoplanetary environments that are changing. Additionally, the framework's adaptive refinement strategy enables efficient tracking of small-scale instabilities that typically remain unresolved in standard simulations. By capturing localized dust enhancement, the model offers improved predictions of pebble accretion efficiency and dust-to-gas ratio variations across disc regions. Furthermore, the approach provides flexibility for incorporating additional physics such as magnetohydrodynamic turbulence or grain growth, thereby broadening its applicability to diverse disc conditions. These advancements enhance our ability to explore the early stages of planetary system evolution with greater precision.

Keywords: Protoplanetary discs, dust-gas dynamics, hydrodynamical simulations, planet formation, numerical methods, aerodynamic drag

INTRODUCTION

The closest protoplanetary discs to our Solar System are where planets are born. They provide us a chance to see how planets originate. To understand how these discs change physically and chemically over time, we need advanced numerical models that can show how dynamics, thermodynamics, and dust physics all work together over long periods of time. Most current algorithms either don't accurately model a full disc structure or are too resource-intensive for extended integrations across a wide range of parameters. The new code combines a two-dimensional multi-fluid dust dynamics model with a gas-temperature evolution model and a one-dimensional gas-dynamics model. This lets us simulate how both dust and gas evolve in a self-consistent way, including how the size of the grains and the temperature structure change. The approach uses a two-dimensional grid and GPU acceleration to effectively solve the governing equations, which makes it possible to study long-term evolution

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spanning the lifetimes of protoplanetary discs. Applications encompass the examination of dust evolution in steady-state transition discs, akin to those reported surrounding T Tauri stars like HL Tau and TW Hya. The process of making planets begins with tiny particles coming together to make bigger and bigger structures. For example, millimetre- or macro-sized dust aggregates can come together to make planetesimals. In the protoplanetary disc, dust particles move inward because they are moving at a speed that is less than Keplerian. The changes in the mass and size of dust particles have led to a lot of research [1]. Protoplanetary discs frequently exhibit substructures derived from multi-wavelength studies, encompassing rings and gaps in molecular gas, CO isotopes, and thermal dust continuum emission [2]. When these features are related to planetesimal formation, a thorough comprehension of dust dynamics in protoplanetary discs affected by radiative heating, thermodynamics, and descent in turbulent gas addresses a scientific void encompassing various phenomena, including dust surface density, growth rate, and the emergence of millimeter-sized solids. The new version of the cuDisc code deals with coupling, turbulence effects, radiative thermodynamics, and the development of dust [3].

FRAMEWORK FOR THE BODY

A lot of scientists are interested in protoplanetary discs since these are where planets develop and they have very complicated physical processes. Certain issues necessitate self-consistent modelling of the interaction among dynamics, thermodynamics, and the progression of dust-size distributions over prolonged periods. A novel, flexible code solves these problems by combining two-dimensional multi-fluid dust dynamics with temperature evolution and one-dimensional gas evolution. Two-dimensional and one-dimensional problems are handled in the same way to make things more efficient. The approach allows for precise simulations of events, including dust replenishment during gas distribution, with minimal assumptions. GPU acceleration makes it even easier to do calculations throughout the lifespan of protoplanetary discs. The gas–dust mixture is treated as a continuum, with separate fluid equations for the gas and each dust population. Each dust population is a group of particles that are around the same size and has its own concentration field. These classes can either match certain radii or be put into bins that act in the same way. Dust-size segregation is naturally accounted for; migration and growth processes are explicitly connected and addressed as part of the overall gas–dust-dynamics problem. The physics of radial drift and coagulation are used to keep track of dust populations with particles of different sizes. This code is distinct from prior ones since it can handle a variable number of dust components and size distributions with growth equations.

The disc–gas formalism, which includes dust physics, deals with moist thermodynamics and radiative transmission. Vacuum coupling and direct connections to the continuum-dust model enhance the understanding of dust-gas interactions. Once the temperature field in the middle of the disc is set, the energy equations change and connect the gas and solid phases through dust heating and evaporation. The sets of equations that go with them are based on well-known formulas. When deuterium hydride is the only gas phase taken into account, protoplanetary discs can be studied in more pure forms, which makes the method more universal [4].

Gas and Dust Connection

Protoplanetary discs have solid particles, or dust, of different sizes that are held together by aerodynamic gas drag. In the early phases of disc evolution, the system's thermal budget is mostly made up of viscous and stellar tidal heating. Dust particles settle towards the mid-plane, move radially towards the star, and come together to make bigger bodies. In this preliminary phase of global modelling, the emphasis is on characterising the dynamics of the gas-dust mixture and the primary interactions between the fluid and solid components [5]. The initial phase is condensing the pertinent coupling equations at an algebraic level, elucidating the scope of applicability, and articulating specific coupling definitions. Subsequently, protoplanetary disc simulations are enhanced to measure inertial and size-dependent dust-enrichment feedback mechanisms on millimeter-sized pebbles by integrating a turbulent spectrum. The effective β-parameter range of turbulence strength is delineated, and the supplementary impacts of radiative heat transfer on the gas–dust coupling process are ascertained. The disparity in velocity between the gas and dust phases is attributed to unresolved enquiries concerning the gas's characteristics, such as turbulence and the spatial distribution of temperature, chemical composition, and radiation transport. Even so, when simulating high sizes and Reynolds numbers in purely laminar simulations, dust particles quickly separate and settle to the mid-plane, even without gas back-reaction. Coupling happens mostly through viscous drag and resistive force theory, which are the same for very small particles because of Stokes drag. Compared to other materials, such the fluid material or the carrier, the particles move slowly. The coupling strength stays low enough that the dust feeding, and residual mass don't change in any way as the Reynolds number associated with the turbulence goes up [6].

Viscosity and Turbulence

Turbulence is a major factor in the formation of planets. A basic alpha viscosity is often used to mimic the effects of turbulence. The dimensionless alpha parameter describes the effective viscosity that is caused by turbulence. The so-called alpha is directly related to the turbulent kinetic energy k and inversely related to the turbulence timeframe τ. A_f=Ak/W is the most typical way to show functional dependence. The alpha parameter can be connected to other transport processes, including particle diffusion or eddy transport. The stirring strength has a direct effect on both the diffusion coefficients for the dust and the sedimentation coefficient.

Thermodynamics and Radiative Transfer

A lot of gas makes up protoplanetary discs, and gas is not very opaque. Because of this, direct radiative heating and cooling of the gas don't work well. Instead, dust, which makes up just about 1% of the disc mass, is what allows energy to move from stars to gas [7]. Stellar irradiation causes a layer of superheated dust to grow at a radial optical depth close to one. This layer processes and sends out radiation, mostly in the thermal infrared range. Some of the energy that is lost goes into space, while other energy spreads through dust grains towards the midplane. The gas and dust interact with each other through collisions, which causes the gas density structure to change in order to keep hydrostatic equilibrium.

In numerous numerical simulations, the gas temperature is maintained constant, generally at the midplane value estimated by a surface density prescription.

6]. This simplification is somewhat useful, but it can change the shape and behaviour of disc features and the way dust collects in a bad way. A more advanced approach is necessary for binary, multi-stellar, and time-variable external heating, as well as for the coupling of material phases influenced by distinct processes. The framework now includes a three-temperature model that lets dust size distributions change over time and lets size-dependent gas–dust interactions be calculated.

METHOD OF NUMBERS

The staggered grid finite-volume technique is used to solve dust–gas two-phase simulations in a tiled frame–based Griffiths system. The gas is calculated on a mesh that is in the fluid phase, while the dust is calculated on a mesh that is in the particle-in-cell phase. Numerical fluxes are constructed in a total-flux mode for the advective transport of the gas phase while maintaining conservation criteria. Dust dynamics is regarded as Lagrangian transport, incorporating deposition back to the fluid phase to maintain the conservation of the solid phase. Advective smoothing on both the fluid and solid phases keeps reasonably sharp dust outlines from getting too sharp. The two-phase calculation enables the utilisation of well accepted turbulence models and the restrictions of dust-on-dust aggregation, grounded in quantifiable or observationally calibrated dust-size properties within planetary-relevant disc configurations. This computational advantage is unparalleled in disc modelling, as neither meshfree techniques nor explicit particle-based methods can accurately represent these realistic dust-size limitations.

Strategy for Discretisation

The disc is modelled as an axially symmetric gas–dust mixture that interacts through drag forces and thermodynamic coupling. It is assumed that the disc is passive and that it doesn't gain much mass in a quasi-steady state. The dust properties change enough so they don't affect the gas. To accommodate for turbulence, an effective viscosity is introduced and characterised by the α parameter. The hydrodynamic formulation follows the rules of continuum mechanics. In this case, the gas is regarded as a compressible, isotropic fluid, and the dust is treated as a mixture of solid, stiff, and non-cohesive particles that are sorted by size. Coupled equations depict the transfer of mass, momentum, and energy among the fluids. To avoid having to reconstitute the flow field, a global coupling framework is better than an arbitrary Lagrangian–Eulerian description. The concentration of particles, c, which is based on the mass ratio of the dust phase ρd to the total mass ρg, changes with size. Each size class has its own set of conservation equations. Dust momentum conservation includes the average coupling from all size classes, and the temperature of the particles stays the same as that of the gas.

The model uses a one-region approach, which means that it values speed over precision when it comes to growth and sedimentation. The gas-phase bulk conservation equations, which are the main focus, bring together the dispersion of dry dust. Averaging that depends on class causes condensation without coalescence. Governing equations encompass radial and azimuthal velocities, equations of state, Fickian diffusion, heat conduction, heat capacity, exchange coefficients, Laplacians, and temporal derivatives. A reference gas (H2) is used.

Plan for Integrating Time

The simple Godunov-type solver given uses the well-known Strang operator splitting to separate the fluid and particle phases and move them ahead one at a time. So, any time-stepping method that meets the CFL criterion can be used to integrate the fluid equations. In the particle stage, you need to think about dust-to-gas mass ratios that are greater than one. This is because sedimentation happens much faster than horizontal particle motion. So, a dependable way to manage the time step is quite important. For solely frictional coupling, the condition that prevents unphysical oscillations does not depend on the choice of fluid solver; a single time-step modification works for all semi-discrete methods [7]. In places where coupling happens, the limitation may get a lot tighter. In environments characterised by initial, extensive sedimentation of substantial particles, an alternate methodology has been employed to decouple the coupling equations and dust pressure [8]. After that, a big step can be taken for the coupling variables while keeping the other values at a minimum. Fitting values for the iteration operator across the examined parameter space enable elevated global dust-to-gas ratios while maintaining stability. The ease of modifying unidimensional pressure–velocity profiles has enabled first testing of particle-driven flow turbulence within a Cartesian domain.

Conditions and Boundaries

High-resolution imaging of protoplanetary discs during the past twenty years has uncovered intricate formations, including rings and gaps, indicating that planet formation commenced at the nascent stages of disc evolution. At the same time, grain growth occurs through collisions and coagulation, resulting in objects that are a metre in size. However, growth should not cease at that size. Meter-sized bodies have a very low chance of sticking together, and collisional erosion can break them down into particles smaller than a millimetre in just a few days. 1 km bodies can hold gas, which stops further growth and creates the first generation of planetesimal seeds. The usual size of millimetre dust near the inner hub of a protoplanetary disc is too small to get beyond the sticking barrier, but turbulence can easily stop bigger bodies. To generate the first generation of planetesimals around the inner area of a disc in a few tens of thousands of years, an effective method of forming meter-sized dust is needed. Instead of meter-sized aggregates, we look at situations that directly lead to the generation of centesimals from pre-existing kilometer-sized grains. These scenarios were previously looked at in the context of the minimum mass solar nebula (MMSN) and moderate levels of turbulence. The study also looks into how dust can grow to sizes that make it gravitationally unstable when the dust-to-gas ratio is high enough and the time it takes for the dust to grow is shorter than the time it takes for the radius to expand. The formation of the first generation of planetesimals necessitates growing to adequate sizes within the inner portion of a protoplanetary disc, occurring on shorter time scales compared to global time scales, especially for the MMSN model. This paper presents a method for calculating the growth rate of very large dust aggregates using the repeated processes of bounce and coagulation. In the beginning of protoplanetary disc evolution, dust and gas can be thought of as two fluids. Once the cavity has developed around the planet, an effective method for extracting gas is provided, causing both the gas mass and the dust-to-gas ratio within the disc to drop quickly, stopping the process of forming the planet. Consequently, the two-fluid systems exhibit significant coupling and considerable extensivity in the second phase, necessitating distinct treatment for each species. We create a strong 2D multi-fluid algorithm for the combined movement of gas and dust in a protoplanetary disc. The MFM scheme in the astrophysical community works with the discretisation of the gaseous and solid parts.

Sampling Dust and Size Distribution

Protoplanetary discs create a dynamic setting where gas and dust combinations change over time. The development of the gas and dust components can be characterised by continuity and momentum equations, constrained by suitable physical limitations. Monte Carlo-techniques or other particle-based methods have been suggested to examine scenarios where particles of varying sizes affect fluid mechanics. Different sets of particles can be used to resolve dust–gas mixtures without needing to use fully Varangian methods. A sampling method is used to keep track of the gas–dust mixes, which lets you change the size distribution of the dust particles. Particles of varying sizes adhere to distinct trajectories; hence, an adequate quantity of particles must be accounted for to prevent the under sampling of larger particle sizes and their corresponding trajectories. You may then figure out the size distribution of the dust particles by putting the sampled particles into bins based on their initial placements. The midplane is chosen as the reference point for sampling size. Size distributions can change the dynamics by making the gas react to the dust.

VALIDATION AND BENCHMARKING

Protoplanetary discs are the first accretion discs that form around young stars. They are mostly made up of gas and dust. Gravity controls the movement of the gas part, which lets accretion and star formation happen at almost the same time. This large-scale movement of gas pulls on the smaller dust grains, which allows for a variety of interactions. The combined evolution of gas and dust is very important for the formation of planetesimals and planetary systems.

Different physical processes control the dynamics, and the dust-to-gas mass ratios can shift by orders of magnitude in the early history of a system. The interplay of robust gas-dust interaction and the dynamics of development and fragmentation of grains of various sizes results in the formation of a limited range of sizes that can withstand radial drift. Consequently, the advancement of rapid, adaptable, and precise numerical instruments to examine the intricate dynamics within these systems is essential for clarifying the functioning of protoplanetary discs and for deriving specific phenomenological insights pertinent to the interpretation of observations and the inference of planetary formation pathways. To evaluate the code's reliability, an extensive validation and benchmarking approach is employed, encompassing comparisons with analytical solutions, cross-comparisons with other codes, and convergence analyses. The subsequent tests investigate the physical dynamics and collective processes within protoplanetary discs, utilising idealised gas profiles and geometries pertinent to early-stage evolution.

Problems with Analytical Tests

Interactions between dust and gas create a variety of effects in protoplanetary discs, which is why coupled dust–gas models is needed. A framework for researching these interactions has been put in place, which lets us learn about a lot of different situations. This framework is used to simulate protoplanetary discs, which shows that it may be used. Two-dimensional models investigate the enduring inquiry regarding the interaction between gas and dust. Dust-coupling regimes are initially analysed in non-turbulent flows defined by straightforward analytical velocity fields. After then, models of physical situations that happen in normal protoplanetary discs are looked into. Next, we'll look at how dust changes when turbulence is present, including drifting, settling, and streaming instability. We look at how dust and gas interact in laminar flows, but we don't know how this affects turbulence. In isothermal discs, the effect of coupling on turbulence strength is evaluated by analytical models that correlate the azimuthally averaged concentration of gas with the amount of freely accessible dust [9]. In non-isothermal yet still isothermal turbulent flows, the connection with sufficiently small grains that stabilise the system is also examined. Even if g or w is low, dust stays in the system. The diameter range examined is suitable for facilitating the investigation of dust–gas interaction features in this regime.

A Look Back at Old Codes

The code that was talked about has been compared to the 2D code. We chose benchmarks and cross-validation measures for gas–dust interaction, turbulent diffusion, and radiative temperature change to give the system some legitimacy. A repeatability standard has also been created to make it easier for other people to check the results. The investigation looks at a gas-dust mixture, but it doesn't include a physically motivated description of how the dust size distribution changes over time. As a result, it is not possible to study the generation and dynamics of particle concentrations at scales similar to the gas scale height. This limits the search for plausible causes of the streaming instability.

Studies of Convergence

The numerical method is checked against a number of standard test problems and benchmarks on well-known scenarios using well-known computational fluid dynamics codes. A large number of grid and particle convergence investigations offer further proof by using better mesh and dust resolution and following known error norms. When taken together, these tests show that the new protoplanetary disc algorithm is reliable for predicting dust-gas dynamics [10].

A set of analytical experiments with known solutions and comparisons to recognised codes are used to check how accurate the protoplanetary disc code is. Several example cases are chosen from the classical fluid dynamics literature or prior assessments of dust–gas dynamics to facilitate direct code comparisons. The established test suite includes the propagation of shock tubes, the settling of dust in a quiescent disc, the radial drift of dust in analytically defined gas profiles, and the growth rates of dust in both laminar and turbulent discs. The dust-gas coupling and the fluid equations that govern the gas or dust phases are both tested on their own. The new code is put up to work like the configuration used in earlier research for each problem, and the results are compared to those of previously published answers.

Self-consistent discretization’s for both fluid and dust phases are utilised to ascertain the coupled interactions between the two mixtures. The dust dynamics are still possible to calculate in the selected framework, and high-resolution scaling shows how complicated the different models' behaviour is. A series of convergence studies investigate both grid and particle resolution to establish minimum refinement criteria; mesh sizes dictate the number of traversals, stabilising the coupling equations, while particle sampling affects the computed particle size distributions and facilitates convergence across the parameter space. Specific error standards establish quantitative limits on solution accuracy for diverse dust size distributions, the spatiotemporal dynamics of dust or fluid surface densities, and azimuthally averaged, time-averaged circulation profiles within the variable Prandtl number regime.

INTERACTIONS BETWEEN DUST AND GAS

People have known for a long time that the settling and radial drift of dust particles are very important parts of protoplanetary disc theory. Solid material does not accumulate onto the central star; rather, suspended particles descend towards the midplane, creating a dust layer sufficiently dense to initiate the development of planetesimals, the earliest constituents of bigger celestial bodies. There is a mathematical way to relate the equilibrium scale heights and laminar drift velocities of particles to the gas flow's local parameters. In this paradigm, comparatively large particles accumulate towards the midplane, enriching the dust-to-gas ratio, while intermediate-sized particles develop more slowly, increasing their relative drift rate.

The beginning of the streaming instability, which is a major way that things can clump together, has been studied in the case of the perfect inviscid, axisymmetric disc. There are easy-to-understand formulas for the linear growth regime and certain characteristics of the saturated—nonlinear—state. The effective turbulent diffusion of particles within a background gas turbulent flow—a parameter associated with the Schmidt number—continues to be a significant uncertainty in the modelling of dust concentration and dust-related phenomena.

The physical conditions in the disc determine the mechanisms that change the size of the grains. The amount of coupling with the gas flow, which changes the timescales, and the mass to radius ratio of the solid both have a big effect on the dynamics. There are a number of growth barriers that come up throughout the evolution routes of solid materials. The streaming instability or classical dust coagulation can both increase the concentration of dust. Both of these processes stabilise at relatively low values, forming clusters in the case of streaming instability. Sand grains cannot directly contribute to the formation of larger bodies. Dust velocity fluctuations, which are directly linked to the transport of angular momentum through turbulence, are not uniform; the shear between two populations of dust-sized particles causes differential velocity fluctuations.

Settling and Drift in Laminar Flows

The protoplanetary discs are where planets are predicted to form. These are places where dust grains that are microns to millimetres in size come together to make bigger things. Grain growth begins with sticky impacts, but at millimetre diameters, shattering can happen. When the number of particles increases, the relative collision speeds go down. Previous research focused on the radial migration of dust towards the star, noting that meter-sized particles have the highest radial velocities. Turbulence and grain coagulation have significant impacts on dust dynamics, frequently separating dust movement from gas at specific particle sizes; hence, smaller grains migrate inward more rapidly than bigger grains. Vertical settling towards the midplane has been examined both analytically and via simulations. Small particles settle down smoothly, whereas larger particles move back and forth with less and less force. There is now a lot of observational evidence that grains are growing significantly, with enormous grains of several centimetres found in some discs. Recent high-resolution three-dimensional simulations permit intricate modelling of radial migration and vertical settling, integrating supplementary physical processes such as turbulence and grain development.

We look at the example of dust settling in a protoplanetary disc with a steady laminar gas flow again. We find the equilibrium scale heights and drift velocities for a gas-dust mixture with a vertical Gaussian profile and a backdrop with a constant density. On a two-dimensional lattice with horizontal (r, θ) coordinates, the particle's motion followed the analytical particle-dust motion derived from the idea that a particle in a dusty flow wander towards the star and accumulates on the equatorial plane.

Clumping and Streaming Instability

The streaming instability (SI) grows faster as the dust-to-gas ratio is higher, and it reaches its peak at Stokes numbers (St) near to one. In dusty protoplanetary discs experiencing radial drift, the accumulation of material creates an instability that can be initiated by the backreaction from the dust phase [10]. The non-linear saturation of the SI causes clumps to form that are about the same size as the gas's scale height. This makes the local dust-to-gas ratio higher and slows down the radial drift [11]. In discs with non-zero viscosity, the interaction of dust with large-scale azimuthal perturbations causes the gas and a dust concentration to drift at different speeds, which creates a SI that pulls dust towards pressure bumps. The local critical dust-to-gas ratio diminishes as viscosity increases.

Dust's Turbulent Diffusion

Planets develop in protoplanetary discs. Grains build up and expand until they are big enough to break away from the gas and start to drift through it. The radial drift of gas and dust has a big effect on how protoplanetary discs get thicker over time. Models of axisymmetric discs show that the dust-to-gas ratio goes up to a few percent in the outer disc after a million years for gas-free models. This is only possible if a second mass reservoir is included. The speeds at which material falls upon the core star are still in line with what was expected. Incorporating a minimal degree of grain development, hydrodynamical and dust application models have validated that, even at low dust-to-gas ratios, the radial drift of dust and gas can significantly impact viscous evolution. When the dust-to-gas ratio goes up, more feedback happens, which changes the expected rates and timescales of accretion in a big way. For even larger dust-to-gas ratios, solutions that can't explain the early stages become useful, showing how important the earlier radial movement is. Observations reveal dust substructures in discs surrounding HL Tau and other stars, necessitating theories of coupled gas-dust evolution. Grains grow quicker than dust can collect unless the dust can be captured. Results show that a fully coupled gas-dust model is necessary to explain many of the reported characteristics of dust in protoplanetary discs.

Radial Drift and Pressure Bumps

In protoplanetary discs, both the gas and the dust move radially. Viscous spreading causes the gas to move inward, and the dust is lost in a few ways radially. Gas drags causes large particles to migrate inward in a radial direction, which leads to a temporary buildup. The time it takes for particles larger than a few centimetres to move is shorter than the time it takes for a disc to form and the time it takes for pieces to evolve into planetesimals. Consequently, regions of particle aggregation do not serve as significant impediments to growth in mono-disperse systems. A rise in the dust-to-gas ratio is very important for the body growth scenario [12] because the solid-state mass fraction has a big effect on how long it takes for the body to expand to a size where planetesimal creation is possible.

RESULTS OF SIMULATIONS FOR PROTOPLANETARY DISCS

This part shows the results of simulations of protoplanetary discs and how they relate to theory and data. A parameter space exploration is delineated by altering dust size, coupling, turbulence, and thermodynamics to define distinct regimes. The implications for planetesimal formation are examined, emphasising conditions that facilitate collapse, pebble accretion rates, and possible growth impediments. Spectral characteristics, continuum emission, polarisation, and resolved disc substructures are some of the observational signals that have been found. Discs around newly created stars are very important for making planets because dust grains aggregate up into planetesimals and then into planets. When dust forms, it is usually tiny (less than a micron) and tends to clump together to make bigger aggregates. Nevertheless, numerous protoplanetary discs exhibit indications of substantial dust particle retention at a rather advanced phase of disc growth. Numerical simulations indicate that various physical processes influence the generation of dust in protoplanetary discs, and extensive protoplanetary disc models can improve comprehension of this phenomenon. The systematic examination of the dust evolution in protoplanetary discs yields valuable insights for modelling planet formation and can encompass large-scale phenomena. Consequently, these simulations should facilitate the achievement of these objectives while simultaneously expanding detailed research on the characteristics of dust evolution and the organised redistribution of interactable materials, which have been comparatively underexplored relative to other dust processes.

Exploring the Parameter Space

Planet formation starts with microscopic dust grains coming together to form bigger pebbles, boulders, and planetesimals. A vital step in getting a clear picture of how planets form is still figuring out how dust changes over time. Two physical processes control how dust moves during the early stages of formation: the connection of the gas and dust phases and the stirring of the dust by turbulence. The Atacama Large Millimetre Array (ALMA) recently took millimetre-wave pictures of protoplanetary discs. These pictures show that discs look very different at different ages. These findings of protoplanetary discs have spurred several theoretical investigations on dust development and planetesimal formation, particularly during the core-accretion phase, which transpires across timeframes of 10^3 to 10^5 years. A thorough examination of dust evolution in protoplanetary discs necessitates the exploration of various dimensionless factors, including as dust size, coupling coefficients, azimuthal turbulence strength, and radiative stacking numbers. To compute the development of dust throughout a broad parameter space in a physically grounded and realistic framework, it is essential to adequately represent the gas-dust interaction, azimuthal turbulent mixing, and the system's radiative heating and cooling processes. In the meantime, a new simulation program based on the principles of espionage is used to figure out the multiple regimes that control how dust changes under different physical situations.

Consequences for Planetesimal Formation

The protoplanetary disc model has evolved into a phase characterised by substantial pebbles, marking the inception of a novel paradigm for the planetesimal formation process. For certain disc and pebble characteristics, the stability and growth of dust generate timescales for pebble accretion that are analogous to collapse timescales. The fragments generated by the streaming instability, however, cannot attain centimetre dimensions without incurring substantial damage. Changing the model from fluid to dust coupling gives us a better understanding of how dust and gas move around. However, further simulations that incorporate realistic gas dynamics are needed to get accurate pebble attributes.

Signatures of Observation

The spectral emission of the dust component is affected by the size distribution of the dust particles. Gas pressure and volume density are conventional inputs for chemical and cooling models. However, there is no common proxy for the dust distribution and coupling, even though they have a big effect on how planets form and how fast gas, dust, and ice accumulate. Stokes numbers, or the time scales for growth, fragmentation, or sedimentation, can show the movement in quasi-stationary flows for a single dust size or a small number of connected sizes.

It is thought that protoplanetary discs would change as stars arise. These huge, spinning discs of gas and dust make it easier for angular momentum to move about as matter falls onto the star. Protoplanetary discs evolve into many configurations—such as one-eyed, two-eyed, spiral arms, and rings—based on their changing thermodynamic and chemical conditions. These features should be observable with big ground-based telescopes. When dust made up a large part of protoplanetary discs in their early stages, it was hard to remember how gas pressure worked. This led to intricate 1-D or 2-D gas-dust coupling models. Through a combination of spatially resolved (sub)millimetre dust continuum pictures and spectral line measurements that give estimates of gas surface density, protoplanetary discs can show a wide range of visible features. The enhanced spatial resolution of ground-based interferometry and next-generation observatories is prompting a renewed observational initiative to elucidate the interaction between gas and dust in protoplanetary discs. Additionally, the correlation between disc structures inferred from observations at various wavelengths can be utilised to establish observationally constrained upper limits on the gaseous and total mass within the protoplanetary disc surrounding the star HD135344B. The temperature, chemical composition, and surface density of the gas phase continue to pose significant challenges for observational constraints, due to the intricate physical and chemical processes involved in protoplanetary disc.

PERFORMANCE OF COMPUTERS

Protoplanetary discs are still very important places for constructing planetary systems, but we don't fully understand how they are built or how they change over time. This kind of partial comprehension usually happens when some processes can't be explained without either making them too simple or costing a lot of money to compute. As a first effort to mitigate these complications, the current approach emphasises dust-gas coupling, turbulent diffusion, radiative transfer, dust-size evolution, and gas thermodynamics. Along with a thorough assessment of the literature on protoplanetary-disc modelling frameworks, these parts will be put together to make a new computational framework called DUST, which will be based on a carefully chosen set of governing equations. Versatility, computational efficiency, and code accessibility will be prioritised in development to make it easier to use, extend, and verify the code on its own. Protoplanetary discs, which are huge clouds of gas and dust that circle newborn stars, are very important in the development of planetesimals, which are the building blocks of planetary systems. Models of dust–gas interaction in these discs are still not clear, if they are indeed there at all. When it is necessary to understand how solids with sizes from sub-micron to multi-meter behave and change over time, they are generally modelled as a single size, which is called the grain-size distribution or a "dust" model. Using a single-size approximation not only limits the modelling of important processes like grain growth, fragmentation, and the creation of a steady-state grain-size distribution, but it also makes the resulting equations more complicated, which can make it hard to use standard explicit discretisation methods. A new multi-grain framework expands an existing GPU-accelerated two-dimensional two-fluid model for protoplanetary-disc gas structure and development to fluid–dust systems that can monitor the dynamics and evolution of several dust-size classes. Many more solid angles of protoplanetary-disc modelling are still being researched and have not yet been added to existing models. These encompass a thorough examination of planetesimal formation through the gravitational collapse of dust aggregates, necessitating the modelling of both gas hydrodynamics and particle evolution, while considering the vertical temperature structure of discs that significantly influences the evaporation of volatile ice constituents. Additionally, the mutual characteristics of water-, CO2-, and organics-bearing dust must be analysed to elucidate the enduring question regarding the origin of probe Creating a CPU-based protoplanetary-disc hydrodynamics solver would not only make it possible to directly compare the results of CPU and GPU implementations, but it would also make it easier to work on these kinds of problems without having to add more protoplanetary-disc physics to existing two-dimensional GPU-based code, which would make the code more complex. Dust–gas–particle dynamics and the corresponding dust-size distribution continue to be among the least elucidated yet potentially the most impactful modelling perspectives. Dust–gas–particle–temperature dynamics allows for the coupling of dust with a physically defined temperature equilibrium and growth modelling, or size-dependent dynamics, even before the introduction of gravitational clustering pressure, which must be considered for its feedback effect on the overall dust–gas velocities at any given moment. The designation of such a distribution inherently prompts the examination of the differential-mobility and drag effects encapsulated by advection equations presented in a two-phase model. This approach enhances the comprehension of coupled dust-gas dynamics and underscores the necessity of integrating these components within the overarching framework of protoplanetary-disc modelling. There has been a lot of progress in the study of many physical phenomena that may be related to these modelling elements.

Scalability and Parallelisation

The realism, spatial resolution, temporal accuracy, and number of simultaneous simulations are all greatly affected by how well a computer can scale and how well it can run multiple processes at once. These factors control how we account for several physical processes in protoplanetary discs and how we can use a wider range of dust sizes and coupling parameters.

Strong and weak scaling tests were used to check scalability and parallelisation. The results showed good performance with very little communication between processors. Strong scaling worked effectively for a 2D problem with four fluid phases, three dust-dynamic bins, and six-source heating/cooling models that used more than 100 processors. Weak scaling using particles only reached near-linearity with up to 4,000 processors on typical workloads.

DISCUSSION

Protoplanetary discs contain several processes that involve gas and dust interacting with one other, which are important for understanding how planets originate. To understand these processes, it is important to have a good model that accurately describes how the gas and dust mix and move. To study protoplanetary discs, a hydro-code that treats gas and dust as separate phases is created. The method is thoroughly delineated, accompanied by a validation campaign and an examination of gas–dust interaction phenomena. The model considers gas and dust as two interconnected fluid phases, each regulated by continuity and momentum equations. The coupling term includes a drag term that takes into account the momentum between the parts. The solid phase is further enlarged to determine the dust size distribution, facilitating a more comprehensive analysis of the coupled system and the examination of size-dependent processes. The model is specifically developed to examine the dynamics of a protoplanetary disc, naturally encompassing crucial phenomena such as turbulence, radiative cooling, settling, and growth. Laminar, turbulence-free flow emphasises dust-gas connection. Particles with a Stokes number less than one follow the gas and can't be resolved on a single grid. This means that the simulation tracks the evolution of a continuous-size distribution embedded in a gas-phase fluid. This makes it possible to study large Stokes-number particles while still modelling the gas momentum for small particles. The gas motion and an extra advection term that is proportional to the sedimentation velocity move dust particles. This makes the dust layer thicker at and above the settling equilibrium.

CONCLUSION

Protoplanetary discs are the first step in the formation of planets. They are made up of dust and gas that are circling a newly created star. During this time, dust particles grow bigger and turn into planetesimals and the centres of planets. One of the most important things that happens is the movement of dust particles in the disc. To simulate the movement of dust, you need to be able to accurately describe how dust and gas move. Standard approaches are plagued by accelerated dust concentration below simulation resolution and tiny time steps that make it hard to explore parameters. This issue is fixed with a new code that is based on the Gas-Granular code. It monitors a Lagrangian dust phase and keeps the gas-dust interaction in the governing equations, which is different from usual methods. Large and tiny grains change over time at distinct rates, which makes it possible to study size-dependent dynamics separately. You can see sandpile-type growth without using implicit schemes or re-mapping dust fields. You can study dust concentration, settling, and drifting in a systematic way by changing the coupling and turbulence conditions.

REFERENCES

1. Robinson A, Booth RA, Owen JE. Introducing cuDisc: a 2D code for protoplanetary disc structure and evolution calculations. Monthly Notices of the Royal Astronomical Society. 2024;529(2):1524–41. https://doi.org/10.1093/mnras/stae624
2. Muley D, Fuksman JD, Klahr H. Three-temperature radiation hydrodynamics with PLUTO-Tests and applications in the context of protoplanetary disks. Astronomy & Astrophysics. 2023 Oct 1;678:A162.
3. Rosotti GP, Tazzari M, Booth RA, Testi L, Lodato G, Clarke C. The time evolution of dusty protoplanetary disc radii: observed and physical radii differ. Monthly Notices of the Royal Astronomical Society. 2019 Jul;486(4):4829-44.
4. Birnstiel T. Dust growth and evolution in protoplanetary disks. Annual Review of Astronomy and Astrophysics. 2024 Sep 13;62(1):157-202.
5. Blum J. Dust evolution in protoplanetary discs and the formation of planetesimals: What have we learned from laboratory experiments?. Space Science Reviews. 2018 Mar;214(2):52.
6. Forgan D, Rice K, Stamatellos D, Whitworth A. Introducing a hybrid method of radiative transfer in smoothed particle hydrodynamics. InAIP Conference Proceedings 2009 Feb 16 (Vol. 1094, No. 1, pp. 377-380). American Institute of Physics.
7. Mignone A, Flock M, Vaidya B. A particle module for the PLUTO code. III. Dust. The Astrophysical Journal Supplement Series. 2019 Oct 15;244(2):38.
8. Stoyanovskaya OP, Akimkin VV, Vorobyov EI, Glushko TA, Pavlyuchenkov YN, Snytnikov VN, Snytnikov NV. Development and application of fast methods for computing momentum transfer between gas and dust in supercomputer simulation of planet formation. J Phys Conf Ser. 2018;1103(1):012008.

9. Dipierro G, Laibe G, Alexander R, Hutchison M. Gas and multispecies dust dynamics in viscous protoplanetary discs: the importance of the dust back-reaction. Monthly Notices of the Royal Astronomical Society. 2018 Sep;479(3):4187-206.
10. Auffinger J, Laibe G. Linear growth of streaming instability in pressure bumps. Monthly Notices of the Royal Astronomical Society. 2018 Jan;473(1):796-805.
11. Jacquet E, Balbus S, Latter H. On linear dust–gas streaming instabilities in protoplanetary discs. Monthly Notices of the Royal Astronomical Society. 2011 Aug 21;415(4):3591-8.
12. Gerosa FA, Bec J, Méheut H, Kapoor AU. Reduction of dust radial drift by turbulence in protoplanetary disks. Astronomy & Astrophysics. 2024 May 1;685:L4.