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# Rossby Wave Instability in Protoplanetary Disks: Physical Mechanisms and Criteria for Onset

Khatab Khalaf
Department of Physics, College of Science, Maragheh University, Iran
*Corresponding author email: khtabmr116@gmail.com*

**Abstract:**

Protoplanetary disks are the birthplaces of planets and are governed by complex hydrodynamical and physical processes. Among the various instabilities influencing disk evolution, the Rossby Wave Instability (RWI) plays a critical role in generating persistent vortices, which can facilitate planetesimal formation and shape disk structure. This review synthesizes current understanding of the fundamental hydrodynamic equations governing disk dynamics The conditions required for the onset of RWI particularly the behavior of vortensity, extrema, and disk parameters such as aspect ratio and viscosity, that most strongly affect instability That strongly affect instability growth like aspect ratio and viscosity theoretical and observational contexts are discussed, Discussed illuminating the central criteria for RWI and its broader significance in the context of planet formation.

## عدم استقرار موجة روسبي في الأقراص الكوكبية الأولية: الآليات الفيزيائية ومعايير البداية

خطاب عمر خلف
قسم الفيزياء، كلية العلوم، جامعة مراغة، إيران
البريد الإلكتروني للمؤلف المراسل: khtabmr116@gmail.com

**مستخلص:**

الأقراص الكوكبية الأولية هي مهد الكواكب، وتتحكم بها عمليات هيدروديناميكية وفيزيائية معقدة. من بين حالات عدم الاستقرار المتنوعة التي تؤثر على تطور القرص، يلعب عدم استقرار موجة روسبي (RWI) دورًا حاسمًا في توليد دوامات مستمرة، مما يُسهّل تكوين الكواكب الصغيرة ويُشكّل بنية القرص. تُلخص هذه المراجعة الفهم الحالي للمعادلات الهيدروديناميكية الأساسية التي تُنظّم ديناميكيات القرص، والظروف اللازمة لبدء عدم استقرار موجة روسبي – وخاصةً سلوك الدوامة وقيمها القصوى – ومعلمات القرص، مثل نسبة العرض إلى الارتفاع واللزوجة، التي تُؤثر بشدة على نمو عدم الاستقرار. تُناقش السياقات النظرية والرصدية الرئيسية، مُوضحةً المعايير المركزية لعدم استقرار موجة روسبي وأهميته الأوسع في سياق تكوين الكواكب.

## 1. Introduction to Rossby Wave Instability (RWI)

Protoplanetary disks are Protoplanetary disks are complex highly dynamic systems that …dynamic and intricate systems that serve as the cradles of planet formation (Armitage, 2011; Andrews et al., 2020). These disks consist of rotating assemblages of gas and dust encircling young stellar objects, where small solid particles coagulate into planetesimals and, ultimately, planets themselves. The evolution and eventual clearing of protoplanetary Protoplanetary disks evolution and eventual clearing are governed by different physical mechanisms including: viscous accertion, … are governed by diverse physical mechanisms—including viscous accretion, irradiation from the central star, the action of magnetic fields, and various hydrodynamical instabilities (Williams & Cieza, 2011). Of these mechanisms, the Rossby Wave Instability (RWI) The (RWI)emerged as a particularly significant process due to its capacity for generating large-scale, long-lived vortices within the disk (Lovelace et al., 1999; Li et al., 2000; Li et al., 2001). These vortices are fundamental in modifying the disk's structure, facilitating the concentration of solids, and mediating the migration of forming planetary bodies (Barge & Sommeria, 1995; Zhu & Stone, 2014).

RWI becomes especially relevant in disk regions characterized by pronounced radial variations in pressure or surface density. Such gradients typically form at locations influenced by planetary cores, at transitions between "dead zones"—regions with low ionization fractions—and in the inner or outer regions of the disk (Andrews et al., 2009; Flock et al., 2015). These sharp gradients can produce extrema in the disk's vortensity profile, a critical condition for triggering the instability (Lovelace et al., 1999; Li et al., 2001). When the RWI is activated, it channels the disk's shear energy into spiral density waves that are amplified and ultimately evolve into anticyclonic vortices—localized areas of high pressure and converging flow—which can endure for many orbital timescales (Surville et al., 2016).

The field has seen rapid advancement due to the capabilities of new observational facilities, most notably the Atacama Large Millimeter/submillimeter Array (ALMA), which offers unprecedented angular resolution and sensitivity. ALMA observations have revealed a wealth of fine structures within protoplanetary disks, including rings, gaps, spiral arms, and prominent azimuthal asymmetries that manifest as "dust crescents" or arcs (Andrews et al., 2018; van der Marel et al., 2013). Many of these features correspond closely to the results predicted by analytical and numerical studies of RWI-generated vortices (Zhu & Stone, 2014; Lovelace et al., 1999), thereby providing compelling motivation for further modeling and simulation to probe the mechanisms responsible for the emergence and maintenance of these structures.

magnetic fields and the associated magnetohydrodynamic affects are a crucial element in the (MHD) effects. While initial theoretical investigations predominantly assumed idealized, purely hydrodynamic or perfectly conducting ("ideal MHD") conditions, it is now well understood that actual disks are not fully ionized (Armitage, 2011; Bai & Stone, 2013). The complex ionization structure, determined by cosmic rays, stellar X-rays, and thermally driven ionization, leads to substantial spatial variations in the coupling between gas and magnetic fields (Gressel et al., 2015). As a result, so-called non-ideal MHD processes—Ohmic resistivity, the Hall effect, and ambipolar diffusion—must be included, as they describe the partial decoupling or "slippage" of magnetic fields from the neutral disk gas (Bai, 2014). These processes change the redistribution of angular momentum and can strongly influence both the onset and evolution of hydrodynamic instabilities like the RWI (Lesur et al., 2014; Bai & Stone, 2013).

The present review aims to synthesize the state-of-the-art understanding of RWI, with a particular emphasis on the comparative roles of ideal and non-ideal MHD effects. The discussion will begin by establishing the foundational physical structure and dynamics of protoplanetary disks to set the stage for understanding disk instabilities. The theoretical underpinnings of the RWI will then be elaborated, highlighting the nature and implications of vortensity extrema and vortex formation. The review will subsequently address the modeling of RWI under both ideal and non-ideal MHD regimes, systematically exploring how the distinct magnetic effects modify vortex formation, longevity, and the capacity for dust concentration and planet migration facilitation (Faure et al., 2015; Surville et al., 2016). Observational results from ALMA and other facilities, as well as the outcomes of numerical simulations, will be synthesized to underscore the significance and prevalence of RWI-induced features in observed disks. The review concludes with a summary of the outstanding challenges in the field and potential directions for future research, underscoring that unraveling the interplay between RWI, dust dynamics, and magnetohydrodynamic phenomena is fundamental for a comprehensive understanding of planet formation (Bai, 2016; Armitage, 2020).

## 2. Disk Hydrodynamics Fundamental Equations

dynamics of protoplanetary disks are governed by The dynamics of differential equations describing mass, momentum, and energy conservation. For simplicity, we often consider a thin, axisymmetric, and isothermal disk in a steady state.

### 2.1. Continuity Equation

The continuity equation describes the conservation of mass within the disk:

$$\frac{\partial \Sigma}{\partial t} + \nabla \cdot (\Sigma v) = 0 \#(2.1-1)$$

where $\Sigma$ is the surface density and $v$ is the velocity vector.

### 2.2. Momentum Equation

The momentum equation, often expressed in cylindrical coordinates , describes *(r,ϕ,z)* the forces acting on the disk material:

$$\frac{\partial v}{\partial t} + (v \cdot \nabla) v = -\frac{1}{\Sigma} \nabla P - \nabla \Phi + F_v \#(2.2-1)$$

where $P$ is the vertically integrated pressure, $\Phi$ is the gravitational potential, and $F_v$ represents viscous forces.

### 2.3. Ideal Gas Law Equation

For an isothermal disk, the pressure

is related to the surface density and sound speed by the ideal gas law:

$$P = c_s^2 \Sigma \#(2.3-1)$$

where $c_s$ is the isothermal sound speed.

**2.4. Keplerian Angular Velocity Equation**

In the absence of pressure gradients, disk material orbits at the Keplerian angular velocity:

$$\Omega_K = \sqrt{\frac{GM}{r^3}} \#(2.4-1)$$

where $G$ is the gravitational constant and $M$ is the mass of the central star.

## 3. Conditions for RWI, or RWI conditions

The RWI typically arises in regions of the disk where there is a local extremum in the "vorticity", specifically the vortensity, which is defined eq. must be numbered is the epicyclic frequency.

**3.1. Epicyclic Frequency**

The epicyclic frequency, $\kappa$, represents the frequency of radial oscillations of a perturbed fluid element in a differentially rotating disk:

$$\kappa^2 = r\frac{d\Omega^2}{dr} + 4\Omega^2 \#(3.1-1)$$

For a Keplerian disk, $\kappa = \Omega_K$. .

**3.2. Rayleigh Criterion**

The Rayleigh criterion for stability states that a fluid is stable to axisymmetric perturbations if the angular momentum per unit mass, $r^2$, increases outwards:

$$\frac{d(r^2\Omega)}{dr} > 0 \#(3.2-1)$$

The RWI, however, is a non-axisymmetric instability.

**3.3. Papaloizou-Pringle Instability Condition**

justify

**3.4. Vortensity Gradient Condition**

A common condition for the onset of RWI is the existence of a local extremum (minimum or maximum) in the radial profile of the vortensity, $\xi = \frac{\kappa^2}{2\Sigma\Omega}$:

$$\frac{d\ln\xi}{dr} = 0$$

at the instability location#(3.4-1)

This often translates to a condition on the generalized Rayleigh criterion, which takes into account pressure gradients.

## 4. Disk Parameters and Their Influence on RWI

The characteristics of the protoplanetary disk significantly influence the development and strength of the RWI.

### 4.1. Disk Aspect Ratio

The disk aspect ratio, *H/r*, where  is the disk scale height, is a crucial parameter related to the disk's thermal state:

$$\frac{H}{r} = \frac{c_s}{r\Omega_K} \#(4.1-1)$$

Thicker disks (*H/r* larger) tend to be more stable or exhibit different RWI characteristics.

### 4.2. Viscosity Parameter (Alpha-Viscosity)

The turbulent viscosity in protoplanetary disks is often parameterized using the alpha-viscosity prescription:

$$\nu = \alpha c_s H \#(4.2-1)$$

where α is a dimensionless parameter. Higher viscosity tends to suppress RWI by damping wave growth.

### 4.3. Surface Density Profile

The radial profile of the surface densit $\Sigma(r)$  is a key determinant of the vortensity profile and thus the RWI. Common profiles include power laws with exponential cutoffs.

$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-p} \exp\left(-\left(\frac{r}{r_{cut}}\right)^{2-q}\right) \#(4.3-1)$$

where $\Sigma, r, r_{\text{cut}}$, *and* are parameters.

### 4.4. Pressure Bump Characteristics

Pressure bumps, which are local maxima in the pressure profile, are often the sites of RWI. These bumps lead to local minima in the vortensity.

**Table 4.1. Typical Disk Parameters for RWI Studies**

| Parameter | Symbol | Typical Range | Unit | Notes |
|---|---|---|---|---|
| Stellar Mass | $M_*$ | 0.1 - 2.0 | $M_\odot$ | Solar mass |
| Disk Mass | $M_D$ | $10^{-5}$ - $10^{-2}$ | $M_*$ | Relative to stellar mass |
| Inner Disk Radius | $r_{in}$ | 0.1 - 1.0 | au | |
| Outer Disk Radius | $r_{out}$ | 10 - 1000 | au | |
| Aspect Ratio | $H/r$ | 0.03 - 0.1 | dimensionless | Also denoted as $h$ |
| Alpha Viscosity | $\alpha$ | $10^{-4}$ - $10^{-2}$ | dimensionless | Controls turbulent dissipation |
| Surface Density Power Law Index | $p$ | 0.5 - 1.5 | dimensionless | For $\Sigma \propto r^{-p}$ |
| Temperature Power Law Index | $q$ | 0.5 - 1.0 | dimensionless | For $T \propto r^{-q}$ |
| Minimum Vortensity Location | $r_{RWI}$ | Depends on pressure bump location | au | Location where RWI is most likely to occur |

## 5. Numerical Simulations of RWI

Numerical simulations are indispensable tools for studying the non-linear evolution of RWI and its observable consequences. These simulations often employ hydrodynamics codes that solve the equations of motion on a computational grid.

### 5.1. Governing Equations for Simulations

For 2D simulations, the vertically integrated equations are typically used:

$$\frac{\partial \Sigma}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\Sigma v_r)+\frac{1}{r}\frac{\partial}{\partial \phi}(\Sigma v_\phi)=0\#(5.1-1)$$

$$\frac{\partial(\Sigma v_r)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\Sigma v_r^2)+\frac{1}{r}\frac{\partial}{\partial \phi}(\Sigma v_r v_\phi)-\frac{\Sigma v_\phi^2}{r}=-\frac{\partial P}{\partial r}-\Sigma\frac{\partial \Phi}{\partial r}+F_{v,r}\#(5.1-2)$$

$$\frac{\partial(\Sigma v_\phi)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\Sigma v_r v_\phi)+\frac{1}{r}\frac{\partial}{\partial \phi}(\Sigma v_\phi^2)+\frac{\Sigma v_r v_\phi}{r}=-\frac{1}{r}\frac{\partial P}{\partial \phi}-\frac{\Sigma}{r}\frac{\partial \Phi}{\partial \phi}+F_{v,\phi}\#(5.1-3)$$

These equations are solved using numerical methods such as finite differences, finite volumes, or smoothed particle hydrodynamics (SPH).

### 5.2. Boundary Conditions

Appropriate boundary conditions are essential for stable and accurate simulations. Common choices include:

- **Inflow/Outflow Boundaries:** Allowing material to enter or exit the computational domain.
- **Reflecting Boundaries:** Preventing material from crossing the boundary.
- **Wave-Damping Zones:** Gradually absorbing outgoing waves to prevent reflections.

### 5.3. Resolution Requirements

Numerical resolution (number of grid cells or particles) is critical for resolving the small-scale features of RWI. The Jeans length or the acoustic wavelength must be sufficiently resolved.

**Table 5.1. Typical Grid Resolutions for RWI Simulations**

| Simulation Type | Radial Resolution ($N_r$) | Azimuthal Resolution ($N\phi$ ) | Notes |
|---|---|---|---|
| Low Resolution | $256 - 512$ | $512 - 1024$ | For quick surveys, often misses fine structures |
| Medium Resolution | $512 - 1024$ | $1024 - 2048$ | Good for capturing basic RWI features |
| High Resolution | $1024 - 2048+$ | $2048 - 4096+$ | Essential for resolving vortices and fine details |

## 6. Observational Signatures of RWI

The RWI can lead to observable features in protoplanetary disks, providing a link between theoretical models and astronomical observations.

### 6.1. Rings and Gaps

The vortices generated by RWI can trap dust particles, leading to enhancements in dust density that manifest as rings. Conversely, regions cleared of dust can appear as gaps.

### 6.2. Azimuthal Asymmetries (Dust Traps)

The long-lived vortices formed by RWI are excellent pressure maxima, acting as dust traps. This leads to strong azimuthal asymmetries in the dust distribution, often observed as crescent-like structures.

### 6.3. Kinematic Signatures

While more challenging to observe, RWI can induce specific kinematic signatures in the disk, such as localized deviations from Keplerian rotation, which could be detected with high spectral resolution observations.

**Table 6.1. Observed Disks with Possible RWI Signatures**

| Disk Name | Instrument (Example) | Observed Feature (Possible RWI) | Notes |
|---|---|---|---|
| Oph IRS 48 | ALMA | Large azimuthal crescent | Strong candidate for RWI-induced dust trap |
| HD 142527 | ALMA | Large-scale asymmetries | Attributed to combination of RWI and companions |
| MWC 758 | ALMA | Spiral arms, asymmetries | Complex morphology, RWI could play a role |
| LkCa 15 | ALMA | Inner ring, potential gap | Possible RWI due to embedded planet or instability |
| Elias 27 | ALMA | Multiple rings and gaps | Though often attributed to planets, RWI may contribute |

## 7. Connection to Planet Formation

RWI is highly relevant to planet formation theories, particularly in its ability to concentrate solid material.

**7.1. Pebble Trapping**

The pressure bumps and vortices created by RWI act as efficient pebble traps, concentrating centimeter-to-meter sized dust grains. This mechanism can overcome the "meter-size barrier" for planetesimal formation.

**7.2. Enhanced Planetesimal Formation**

By increasing the local density of pebbles, RWI facilitates gravitational collapse and streaming instability, leading to accelerated planetesimal formation.

**7.3. Giant Planet Formation Sites**

The enhanced density of solids in RWI-induced dust traps could also provide a favorable environment for the core accretion of giant planets.8. Conclusion and Future Work

The Rossby Wave Instability is a robust mechanism for generating substructures in protoplanetary disks, providing a compelling explanation for many of the observed features. Its role in concentrating solids makes it a key process in modern planet formation theories.

Further research is needed to fully understand:

- The interplay between RWI and oth-

er instabilities (e.g., magnetorotational instability, gravitational instability).
- The long-term evolution and dissipation of RWI-induced structures.
- The observational verification of kinematic signatures of RWI.
- The impact of RWI on the formation of diverse planetary systems.

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## Appendix A: Derivation of Epicyclic Frequency

The epicyclic frequency, $\kappa$, is derived from the linearized equations of motion for a fluid element perturbed from a circular orbit in an axisymmetric potential.

Consider a fluid element in a differentially rotating disk at radius $r_0$ with angular velocity $\Omega_0 = \Omega(r_0)$ .. If perturbed slightly to $r = r_0 + \delta r$ and $\phi = \phi_0 + \delta$, the equations of motion in a rotating frame are:

$$\ddot{r} - r\dot{\phi}^2 = -\frac{\partial \Phi}{\partial r} - \frac{1}{\Sigma}\frac{\partial P}{\partial r} \#(A-1)$$

$$\frac{1}{r}\frac{d}{dt}\left(r^2\dot{\phi}\right) = -\frac{1}{\Sigma r}\frac{\partial P}{\partial \phi} - \frac{1}{r}\frac{\partial \Phi}{\partial \phi} \#(A-2)$$

For an unperturbed circular orbit, $\dot{r} = 0, \dot{\phi} = \Omega(r)$ and the radial force balance is:

$$-r\Omega^2 = -\frac{\partial \Phi}{\partial r} - \frac{1}{\Sigma}\frac{\partial P}{\partial r} \#(A-3)$$

Linearizing Equations (A-1) and (A-2) about the unperturbed state, assuming $\frac{\partial P}{\partial \phi} = and \frac{\partial \Phi}{\partial \phi} = 0$ for axisymmetric background:

$$\delta\ddot{r} - 2\Omega_0 r_0 \delta\dot{\phi} - \Omega_0^2 \delta r - \frac{\partial(\Omega^2 r)}{\partial r} \backslash bigg|_{r_0} \delta r = \cdots \#(A-4)$$

The full derivation involves careful linearization and substitution, leading to:

$$\delta\ddot{r} + \kappa^2 \delta r = 0 \#(A-5)$$

where $\kappa^2$ is identified as:

$$\kappa^2 = \frac{1}{r}\frac{d(r^2\Omega)^2}{dr} = r\frac{d\Omega^2}{dr} + 4\Omega^2 \#(A-6)$$

For a Keplerian disk, $\Omega = \Omega_K = \sqrt{GM/r^3}, so \Omega^2 = GM/r \cdot Then \frac{d\Omega^2}{dr} = -3GM/r$. Substituting this into Equation (A-6):

$$\kappa^2 = r\left(-\frac{3GM}{r^4}\right) + 4\left(\frac{GM}{r^3}\right) = -\frac{3GM}{r^3} + \frac{4GM}{r^3} = \frac{GM}{r^3} = \Omega_K^2 \#(A-7)$$

Thus, for a Keplerian disk, $\kappa = \Omega_K$.

## Appendix B: Parameters for a fiducial RWI Simulation

This appendix provides a detailed list of parameters often used in a fiducial numerical simulation of the Rossby Wave Instability in a protoplanetary disk.

**Table B.1. Fiducial Simulation Parameters for RWI**

| Parameter | Symbol | Value | Unit | Notes |
|---|---|---|---|---|
| Stellar Mass | $M_*$ | 1.0 | $M_\odot$ | Solar Mass |
| Inner Radial Boundary | $r_{in}$ | 0.5 | au | Inner edge of computational domain |
| Outer Radial Boundary | $r_{out}$ | 2.5 | au | Outer edge of computational domain |
| Number of Radial Cells | $N_r$ | 512 | dimensionless | |
| Number of Azimuthal Cells | $N$ | 1024 | dimensionless | |
| Aspect Ratio | $H/r$ | 0.05 | dimensionless | Assumed constant throughout the disk |
| Alpha Viscosity | α | $1\times10^{-4}$ | dimensionless | Low viscosity to allow instability |
| Initial Surface Density at $r_0$ | $\Sigma_0$ | $1.0\times10^{-3}$ | $M_*$ /au$^2$ | Normalization constant for surface density |
| Surface Density Power Index | $p$ | 1.0 | dimensionless | For $\Sigma \propto r^{-p}$ |
| Pressure Bump Location | $r_{bump}$ | 1.0 | au | Radial location of the pressure maximum |
| Pressure Bump Width | $\Delta r_{bump}$ | 0.1 | au | Characteristic width of the pressure bump |
| Pressure Bump Amplitude Factor | $A_{bump}$ | 1.5 | dimensionless | Factor by which pressure is enhanced at the bump |
| Equation of State | | Isothermal | | $P = c_s^2 \Sigma$ |
| Gravitational Potential | Φ | Keplerian | | From central star only |
| Computational Time | $t_{sim}$ | 100 | Orbital periods at | To allow for growth and saturation of RWI |
| Boundary Conditions (Inner) | | Wave Damping | | Prevents reflections from inner boundary |
| Boundary Conditions (Outer) | | Wave Damping | | Prevents reflections from outer boundary |

The pressure bump profile can be implemented as a Gaussian modification to the otherwise power-law pressure:

$$P(r) = P_0\left(\frac{r}{r_0}\right)^{-(p+2)}\left[1 + A_{bump}\exp\left(-\frac{\left(r - r_{bump}\right)^2}{2\left(\Delta r_{bump}\right)^2}\right)\right]\#(B-1)$$

where \$P_0\$ is a normalization constant and \$P=c_s^2 \Sigma\$.

**Appendix C: Glossary of Terms**

For clarity and ease of reference, a glossary of key terms used throughout this document is provided below.

**Table C.1. Glossary of Key Terms**

| Term | Definition |
|---|---|
| ALMA | Atacama Large Millimeter/submillimeter Array; a powerful radio telescope used for observing protoplanetary disks. |
| Aspect Ratio (\$H/ r\$) | The ratio of the disk scale height (\$H\$) to the radial distance (\$r\$), indicating disk thickness. |
| Core Accretion | A leading theory of giant planet formation where a solid core forms first, then accretes a gas envelope. |
| Dust Trap | A region in a protoplanetary disk where solid particles (dust) become concentrated, often due to pressure maxima. |
| Epicyclic Frequency (\$κ\$) | The frequency of small radial oscillations of a perturbed fluid element in a differentially rotating disk. |
| Gaps | Annular regions in a disk with reduced gas and/or dust density. |
| Hydrodynamics | The study of the motion of fluids and the forces acting on them. |
| Isothermal Disk | A disk where the temperature is constant throughout, or follows a pre-scribed temperature profile, simplifying the energy equation. |
| Keplerian Orbit | An orbit described by Kepler's laws, characteristic of objects moving under the influence of a central gravitational force. |
| Meter-Size Barrier | The theoretical challenge in planet formation where meter-sized peb-bles experience strong radial drift, preventing their growth. |
| Papaloizou-Pringle Instability | A global hydrodynamic instability that can occur in differentially rotat-ing fluid systems with specific angular momentum profiles. |

| Term | Definition |
|---|---|
| Pebble Trapping | The process by which small solid particles (pebbles) are concentrated in regions of pressure maxima, aiding planet formation. |
| Planetesimal | A small celestial body (typically few km to few hundreds of km) that is a building block of planets. |
| Protoplanetary Disk | A rotating circumstellar disk of gas and dust f rom which planets form. |
| Pressure Bump | A localized region in a disk where the gas pressure is higher than its surroundings. |
| Rings | Concentric enhancements in the dust and/or gas density within a protoplanetary disk. |
| Rossby Wave Instability (RWI) | A hydrodynamic instability in differentially rotating fluid systems, leading to the formation of long-lived vortices at vortensity extrema. |
| Surface Density (Σ) | The mass per unit area of a disk. |
| Vortensity (ξ) | A measure related to the vorticity of a fluid, often defined as $\frac{\kappa^2}{2\Sigma\Omega}$ in disk physics. |
| Vortices | Swirling regions of fluid motion, often formed by instabilities like RWI, capable of trapping dust. |
| Alpha-Viscosity (α) | A dimensionless parameter representing the effective turbulent viscosity in astrophysical disks. |