Катастрофические события в протопланетных дисках и их наблюдательные проявления

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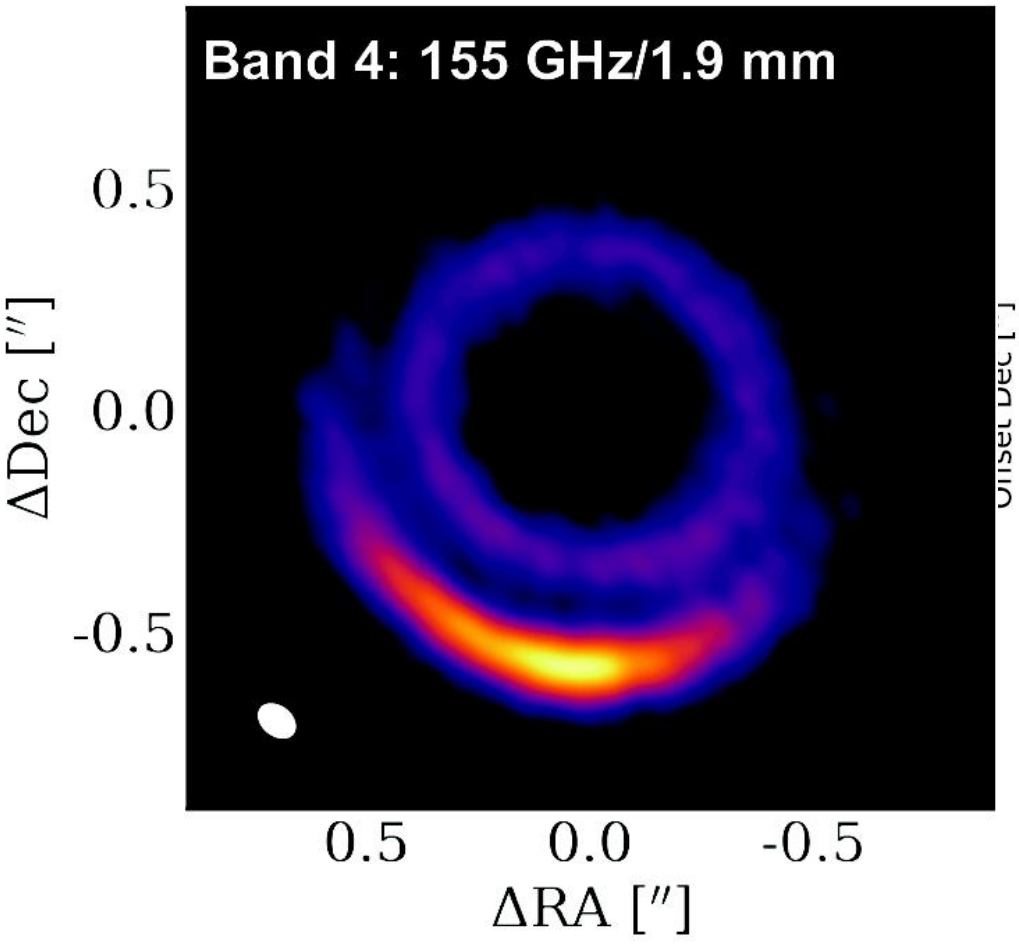
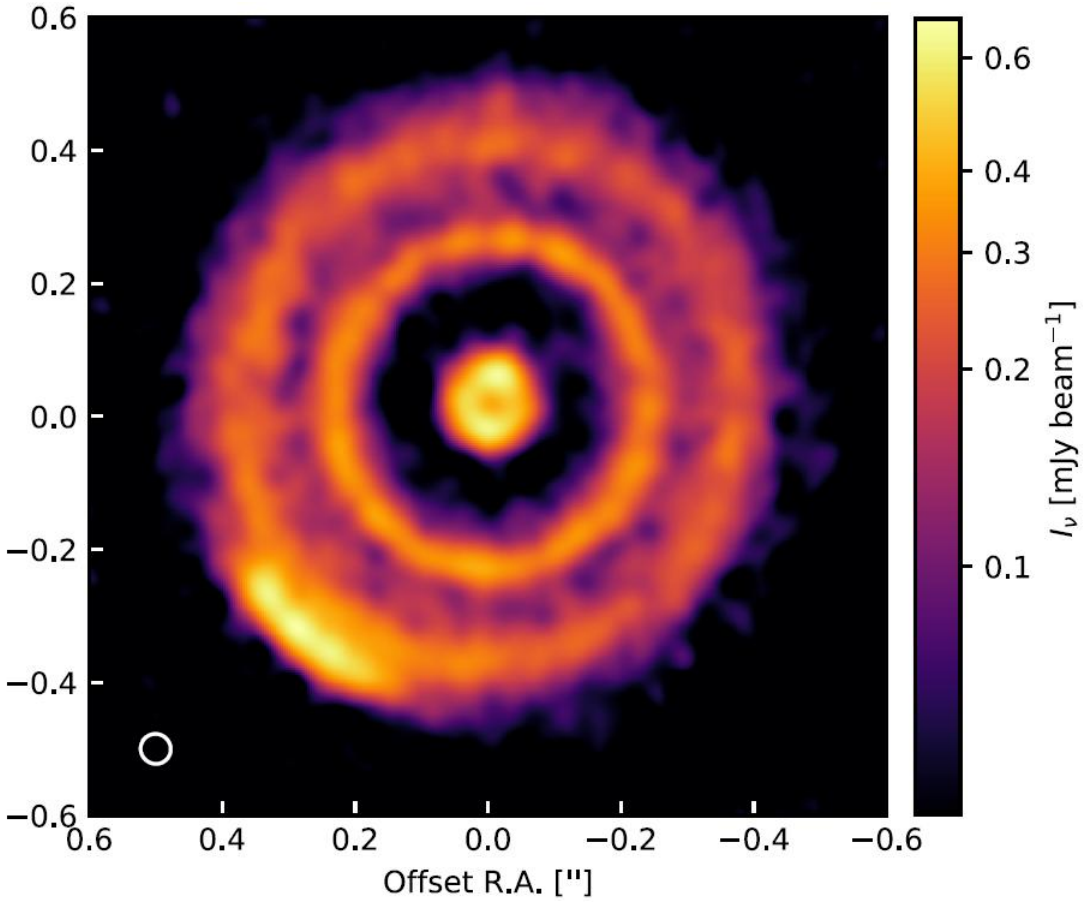
Крымская астрофизическая обсерватория РАН

HD 135344B, Cazzoletti et al., 2018

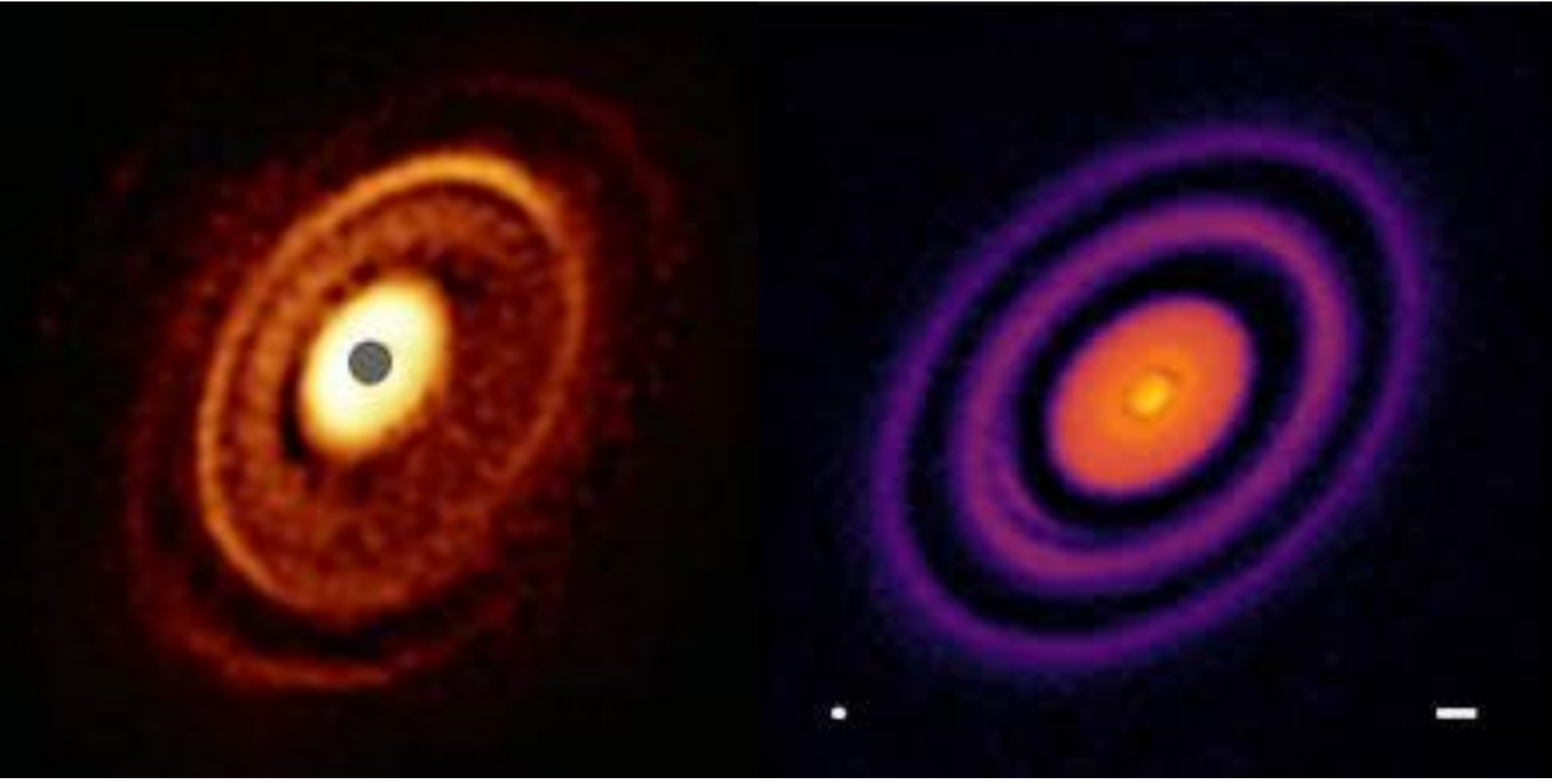


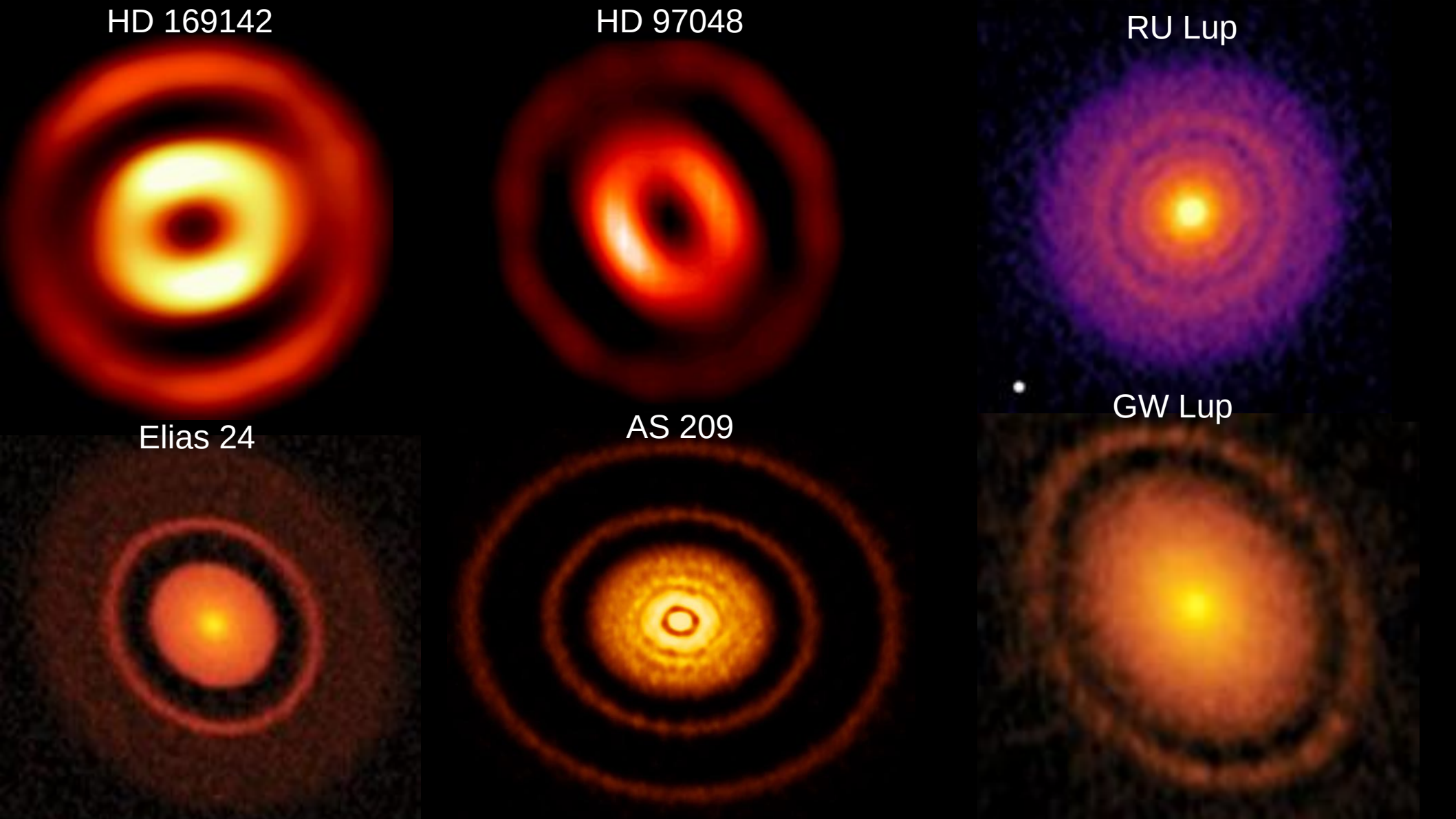
HD 143006, Perez et al., 2018



RXJ 1615, Avenhaus et al., 2018

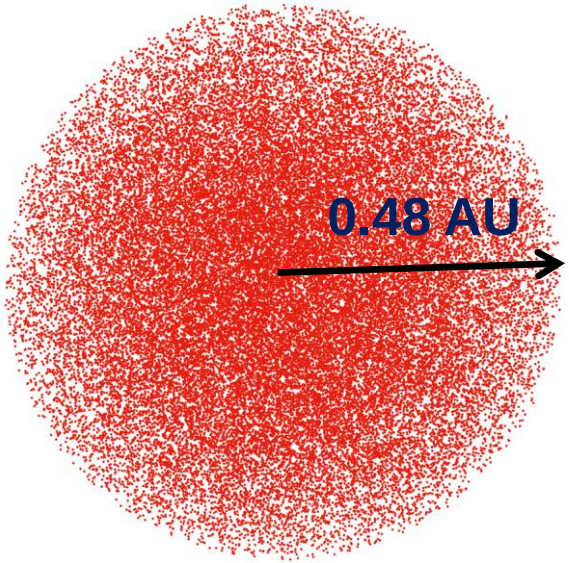
HD 163296, Huang et al., 2018




HD 169142
HD 97048
RU Lup
Elias 24
AS 209
GW Lup


Jackson & Wyatt 2012; Genda et al. 2015b

Модель



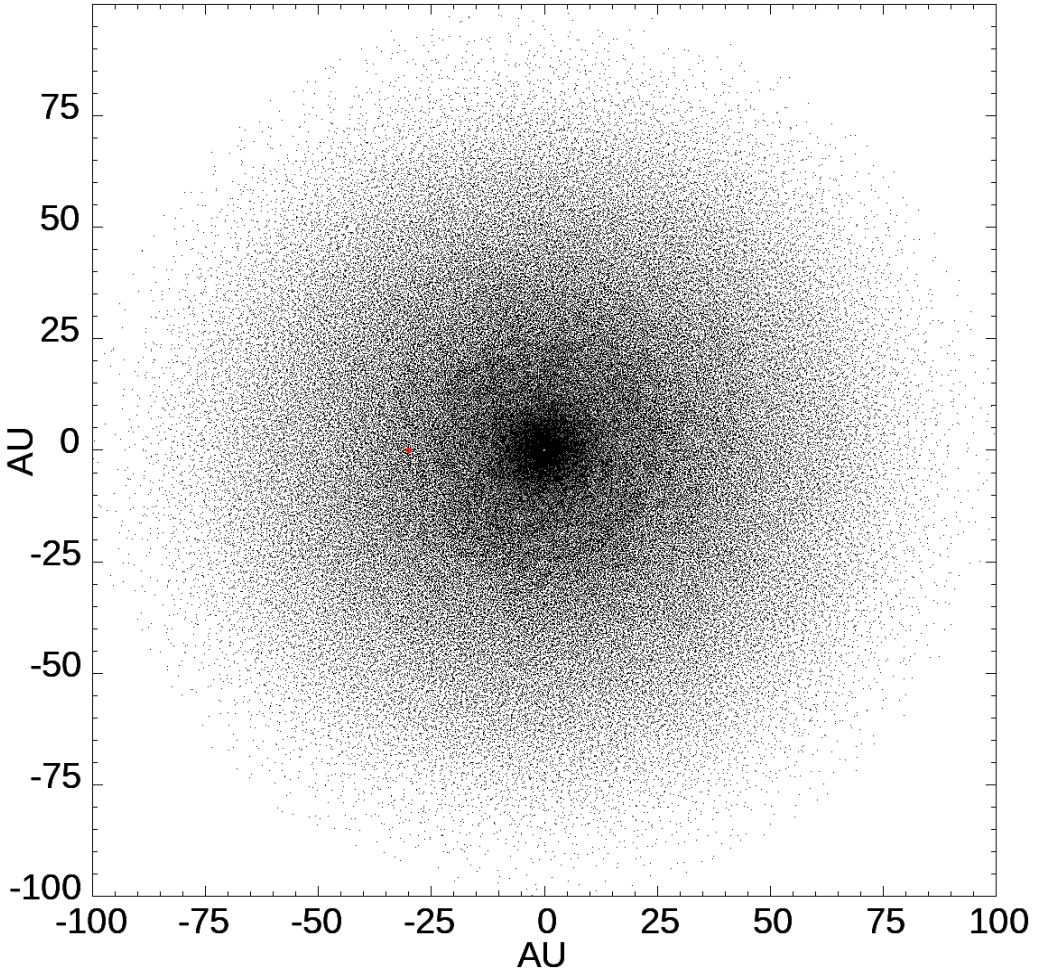
$$\rho_w(x) \propto e^{-x}$$

$$\rho_d = 1\ \mathrm{g\ cm^{-3}}$$

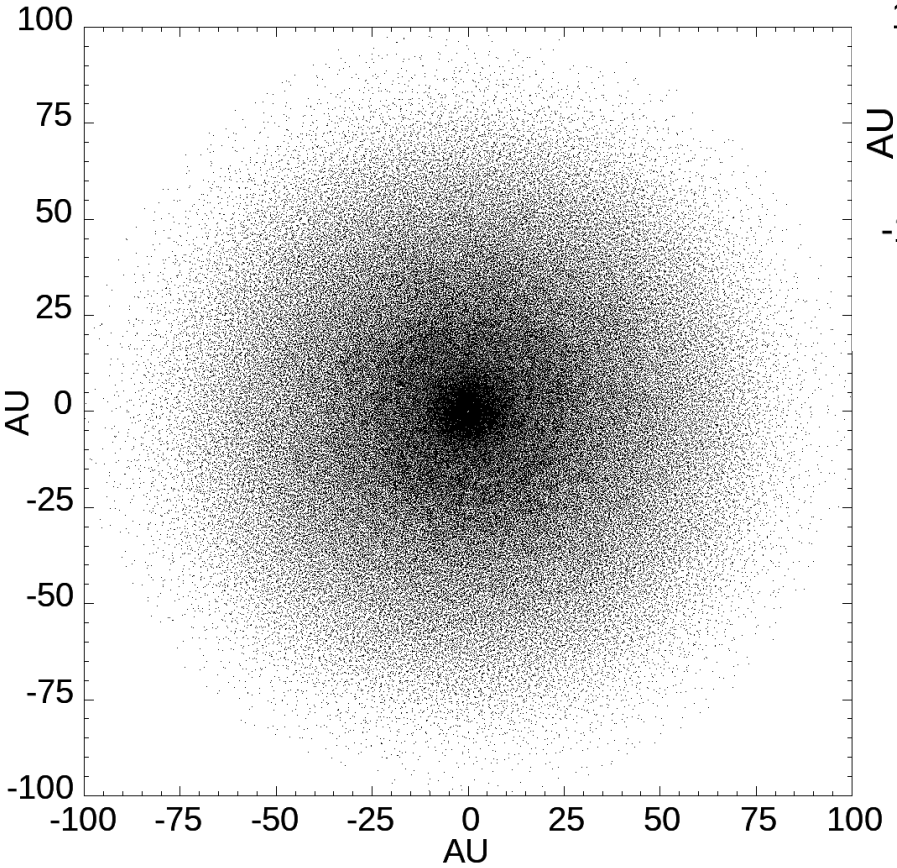
10 мкм, 100 мкм и 1 мм

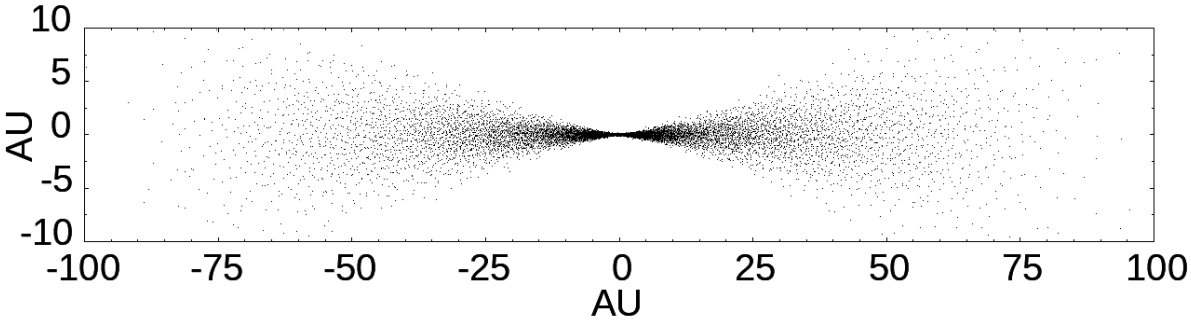
$M_w = 4 \cdot 10^{25}$ г,

$V_e = 50 \pm 50$ м/с



Параметры диска





$$M_{\rm disk} = 0.01 M_\odot \qquad M_{\rm dust} = 10^{-4} M_\odot$$

$$\rho(r, z) = \frac{\Sigma_0}{\sqrt{2\pi}\, H(r)} \left(\frac{r}{r_{\rm in}}\right)^{-1.5} e^{-\frac{z^2}{2H^2(r)}}$$

$$H(r) = \sqrt{\frac{\kappa T_{\rm mid}(r)\, r^3}{G M_* \mu m_H}} \qquad T_{\rm mid}(r) = \sqrt[4]{\frac{\phi}{4}} \sqrt{\frac{R_*}{r}}\, T_*$$

(Dutrey et al. 1994; Chiang & Goldreich 1997; Dullemond & Dominik 2004).

Уравнения для пыли и для газа

$$\frac{\partial \rho_{\rm g}}{\partial t} + \nabla \cdot \left(\rho_{\rm g} \mathbf{v}_{\rm g}\right) = 0,$$

$$\frac{\partial \rho_{\rm d}}{\partial t} + \nabla \cdot \left(\rho_{\rm d} \mathbf{v}_{\rm d}\right) = 0,$$

$$\rho_{\rm g}\left(\frac{\partial \mathbf{v}_{\rm g}}{\partial t} + \mathbf{v}_{\rm g} \cdot \nabla \mathbf{v}_{\rm g}\right) = \rho_g \nabla\phi + K(\mathbf{v}_{\rm d} - \mathbf{v}_{\rm g}) - \nabla P_{\rm g} + \mathbf{F}_\nu,$$

$$\rho_{\rm d}\left(\frac{\partial \mathbf{v}_{\rm d}}{\partial t} + \mathbf{v}_{\rm d} \cdot \nabla \mathbf{v}_{\rm d}\right) = \rho_d \nabla\phi - K(\mathbf{v}_{\rm d} - \mathbf{v}_{\rm g}),$$

$$P = c^2(R)\rho_{\rm g} \qquad K \equiv \frac{\rho_{\rm d}}{t_{\rm stop}} \qquad t_{\rm stop} = \frac{s\rho_{\rm s}}{c_{\rm s}\rho_{\rm g}}$$

Метод SPH (Lucy,1977; Gingold & Monaghan, 1977)

Сглаженное значение

$$A_I(\vec{r}) = \int A(\vec{x}) W(\vec{r} - \vec{x}; h) d\vec{x}$$

Ядро интерполяции

$$W = \frac{1}{\pi h^3} \begin{cases} 1 - 1.5\,q^2 + 0.75\,q^3, & 0 \le q \le 1\,, \\ 0.25\,(2-q)^3, & 1 \le q \le 2\,, \\ 0, & q > 2\,, \end{cases}$$

Свойства ядра

$$\int W(\vec{r} - \vec{x}; h) d\vec{x} = 1$$

$$\lim_{h \to 0} W(\vec{r} - \vec{x}; h) = \delta(\vec{r} - \vec{x})$$

h — **длина сглаживания**

q = r/h

Интерполяционная сумма

$$A_S(\vec{r}_i) = \sum_j \frac{A(\vec{r}_j)}{n(\vec{r}_j)} W(\vec{r}_i - \vec{r}_j; h)$$

Производная

$$\nabla A_S(\vec{r}) = \sum_j \frac{A(\vec{r}_j)}{n(\vec{r}_j)} \nabla W(\vec{r}_i - \vec{r}_j; h)$$

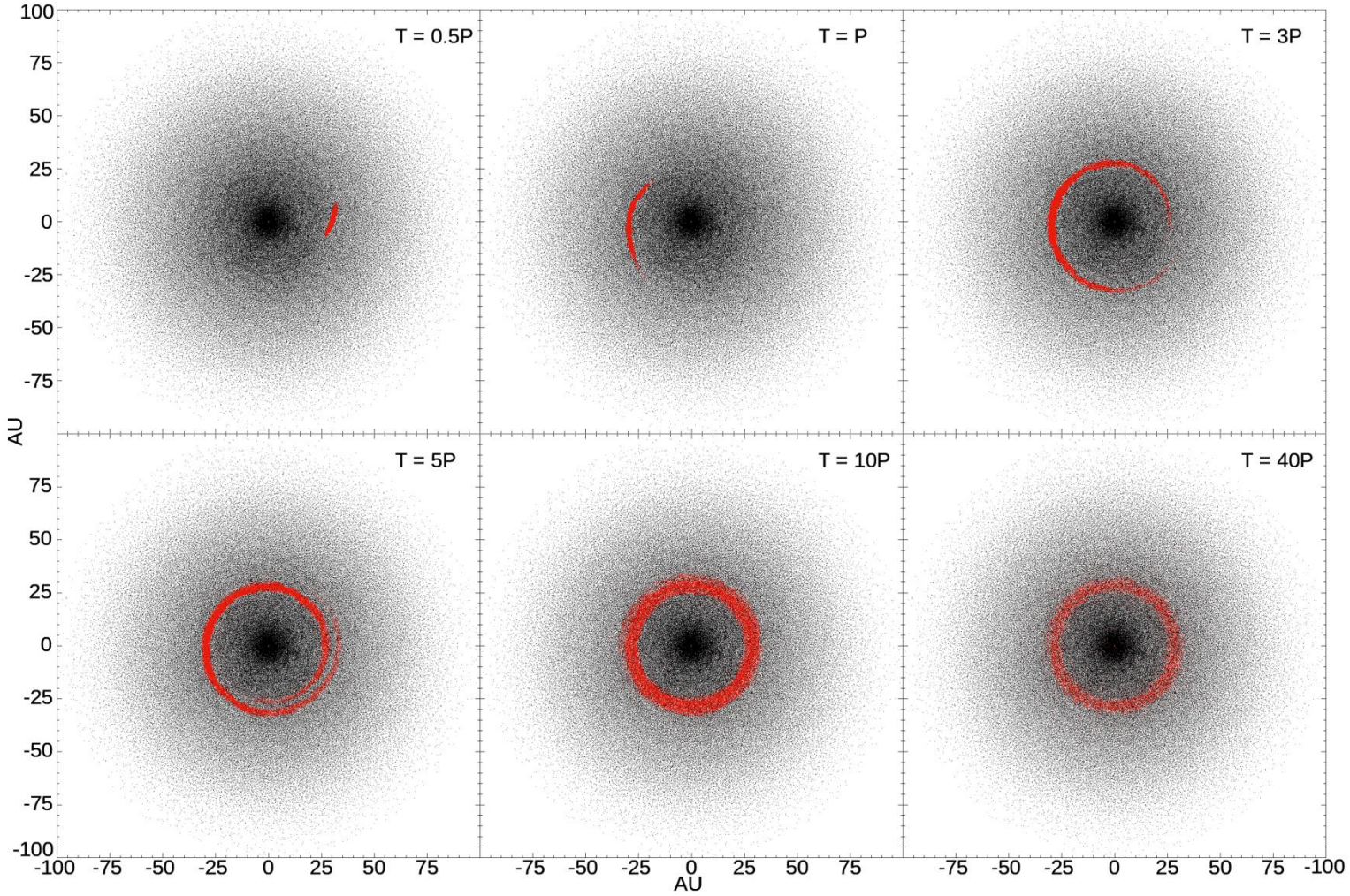
Моделирование газа

GADGET-2 (Springel, 2010)
http://www.mpa-garching.mpg.de/gadget/
модификация Демидова (2016)

Моделирование пыли

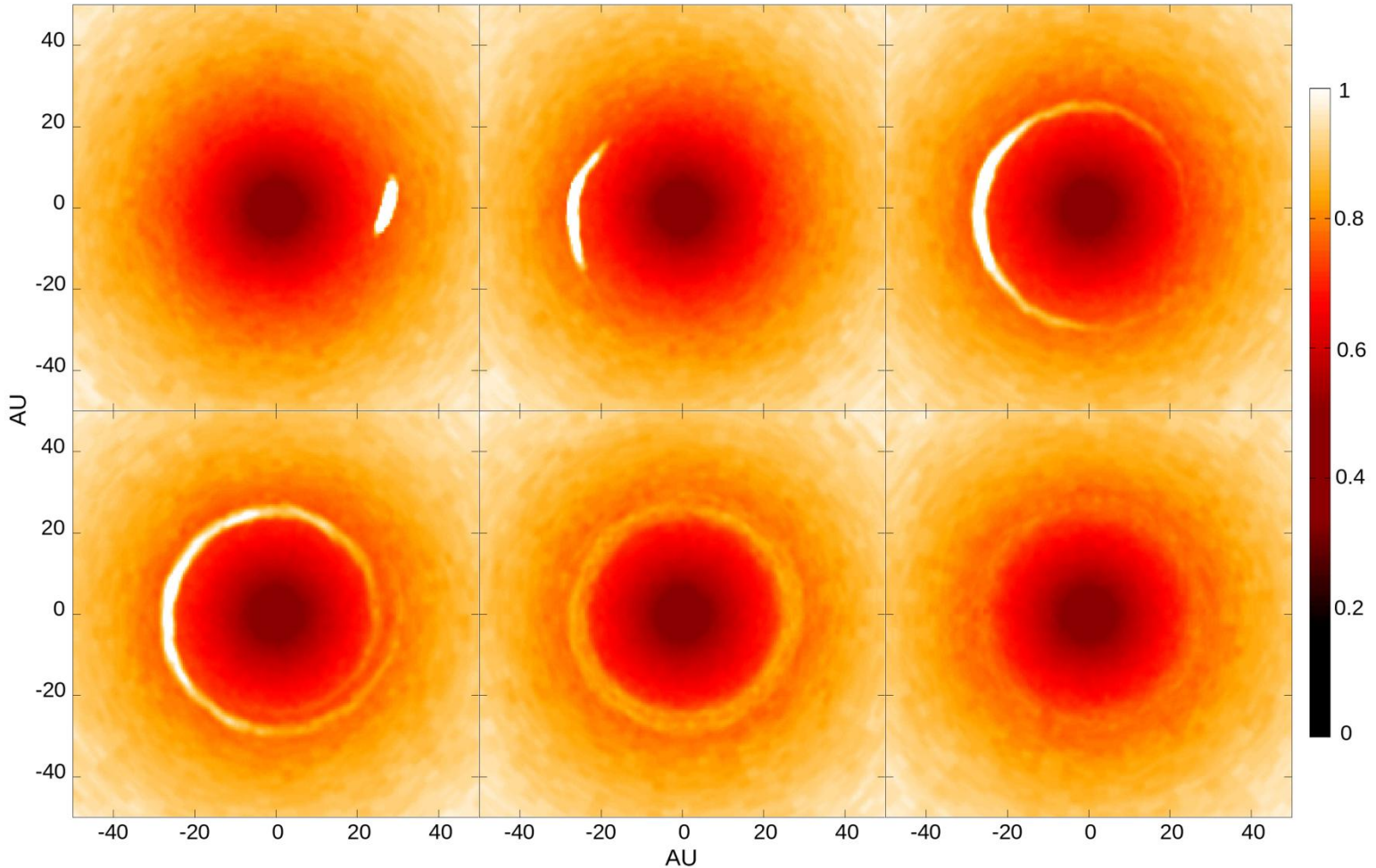
Laibe & Price (2014)

Результаты расчетов



Изображения

(RADMC-3D http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/)



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Catastrophic Events in Protoplanetary Disks and Their Observational Manifestations

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Abstract

Observations of protoplanetary disks with high angular resolution using an ALMA interferometer showed that ring-shaped structures are often visible in their images, indicating strong disturbances in the disks. The mechanisms of their formation are vividly discussed in the literature. This article shows that the formation of such structures can be the result of destructive collisions of large bodies (planetesimals and planetary embryos) accompanied by the formation of a large number of dust particles, and the subsequent evolution of a cloud of dust formed in this way.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300); Planetary system formation (1257); Hydrodynamical simulations (767)

1. Introduction

One of the most interesting results obtained using ALMA and VLT is the detection of substructures on images of protoplanetary disks observed with high angular resolution (see, e.g., van Boekel et al. 2017; Avenhaus et al. 2018; Benisty et al.

obliquity of Uranus is also connected with the giant impact (e.g., Slattery et al. 1992).

It is obvious that the collisions of such large bodies, which result in the formation of a dust cloud, should be accompanied by flashes in the infrared region of the spectrum. In this

Обоснование модели

Планета может способствовать выбросу планетезималей на периферию (Batygin & Morbidelli, 2013; Morrison & Malhotra, 2015).

Столкновение планетезималей естественный процесс для протопланетных дисков (Meng et al., 2014; Genda et al., 2015);

Начальная масса столкнувшихся тел может быть в 10 раз меньше массы сгустка;

События в Солнечной системе: образование Луны (Cameron & Ward, 1976), образование системы Плутон-Харон (Canup 2005, Stern et al., 2006), наклонение оси Урана (Slattery et al. 1992);