SF2A 2021
A. Siebert, K. Baillié, E. Lagadec, N. Lagarde, J. Malzac, J.-B. Marquette, M. N'Diaye, J. Richard, O. Venot (eds)

GAS AND DUST EMISSION OF A PROTOPLANETARY DISC WITH AN ECCENTRIC JUPITER INSIDE A CAVITY

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Abstract. This conference proceeding summarises the results of our recently published work, where we investigated the observational signatures of a warm Jupiter that becomes eccentric after migrating into a low-density gas cavity in its protoplanetary disc. In this scenario, the wakes of the eccentric planet, and the fact that the gas in the cavity becomes eccentric, cause the formation of large-scale asymmetries in CO (3-2) integrated intensity maps as well as distortions of iso-velocity contours in CO (3-2) velocity maps inside the cavity. Both features are found to be detectable for an angular resolution and a sensitivity comparable to those achieved in ALMA disc gas observations. With too little dust left inside the cavity, the near-infrared polarized intensity and the sub-millimetre continuum emission mostly arise from outside the cavity and show no significant differences when the planet is eccentric or still circular inside the cavity.

Keywords: planetary systems: protoplanetary discs, planet-disc interactions, planets and satellites: formation, hydrodynamics, radiative transfer.

1 How did most warm Jupiters become eccentric?

The starting point of this work is the possible origins for the eccentricity of the warm Jupiters. These are the planets spotted by the red ellipse in the diagram shown in Fig. 1. They have a mass comparable to that of Jupiter, an orbital period longer than 100 days, and feature a substantial median eccentricity of approximately 0.25. A natural question is how most warm Jupiters acquired such level of eccentricity. In Debras et al. (2021), we have recently revisited the possibility that a massive planet could become eccentric during its early orbital evolution in its protoplanetary disc. We have found that the presence of a low-density gas cavity in the disc, carved for instance by stellar photoevaporation or disc magnetized winds, can grow the eccentricity of Jupiter-mass planets that migrated into the cavity to values as high as 0.3–0.4. Other mechanisms can grow the eccentricity of massive planets before or after the dissipation of the protoplanetary disc, and we refer the reader to the introductions of Debras et al. (2021) and Baruteau et al. (2021).

Cavities are often observed in protoplanetary discs. More frequently in the dust emission (such discs are commonly referred to as transition discs), but also in the gas emission (e.g., Carmona et al. 2017; Rivière-Marichalar et al. 2020). This suggests that the presence of a gas cavity could constitute a generic scenario to grow the eccentricity of massive planets (Debras et al. 2021). From the idea that warm eccentric Jupiters could indeed arise because of the presence of a gas cavity in their parent disc, we have investigated in Baruteau et al. (2021) what observational signatures such planets would entail in the gas and dust emission of their disc. The results of this work are briefly described below.

2 An eccentric warm Jupiter in a disc cavity

We carried out two-dimensional (2D) gas and dust hydrodynamical simulations modelling the interaction between a 2 Jupiter mass planet, its protoplanetary disc, and a 2 Solar mass star. The disc features a $\sim$30 au wide

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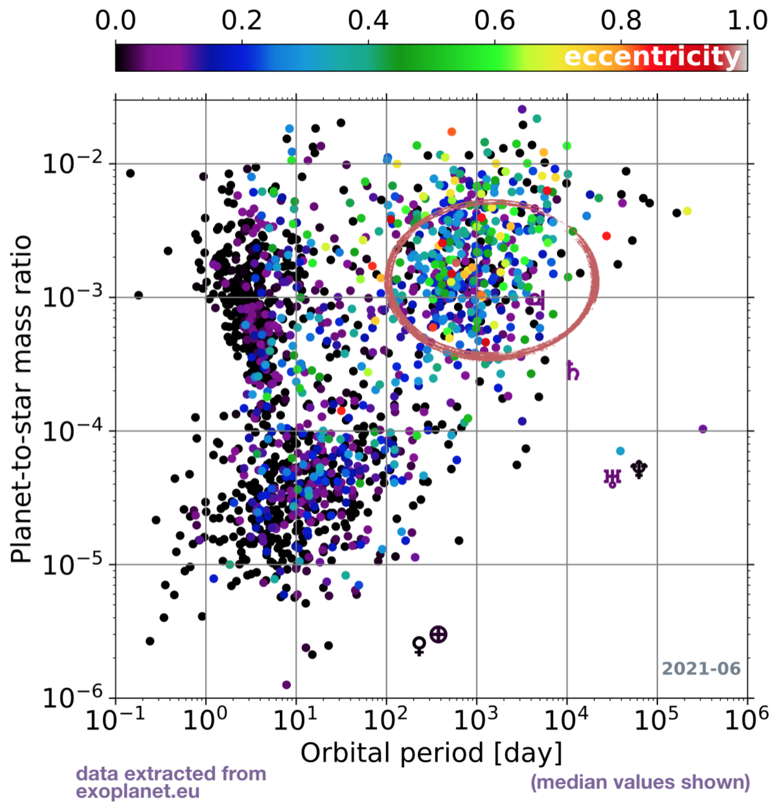

Fig. 1. Eccentricity of the exoplanets and the planets in the Solar System, as a function of planet-to-star mass ratio and orbital period (diagram updated from Debras et al. 2021). The red ellipse shows the group of planets commonly referred to as warm Jupiters.

cavity wherein the decrease in the gas surface density is maintained by a jump in the disc turbulent viscosity. All details about the physical model and numerical set-up can be found in Section 2 of Baruteau et al. (2021).

The planet starts its orbital journey slightly outside the cavity and progressively migrates into it. When the planet has drifted sufficiently far from the outer edge of the cavity, its eccentricity grows due to the dominance of the eccentric resonances of the disc-planet interaction. In our model, the planet reaches in about 4 Myr a near steady state eccentricity of approximately 0.25, which is close to the median eccentricity of the warm Jupiters. The top-left panel in Fig. 2 displays the gas surface density on a logarithmic scale when the planet has reached a near maximum eccentricity and is close to the apocentre of its orbit. We see that the gas density around the planet orbit displays strong asymmetries due to the shocks induced by the planet wakes (here, the gas density is about ten time smaller behind the planet along its orbit than in front of it). Asymmetries with a similar contrast in the gas density are obtained whether the planet is close to its apocentre, like in the figure, or at a different orbital phase of the planet.

To examine what implications our eccentric planet has on the gas and dust emission of its disc, we post-processed the results of the hydrodynamical simulations with gas or dust radiative transfer calculations. The disc is assumed to be located at 100 pc and to have a 30° inclination relative to the sky-plane (for further details about the radiative transfer calculations, like the inclusion of photodissociation by UV irradiation for the gas calculations, the reader is referred again to Baruteau et al. 2021).

First, for the gas we looked at the J=3→2 rotational line emission for several CO isotopologues in the sub-millimetre, and in the bottom row of panels in Fig. 2 we show results for ^{12}CO at the same time as the gas surface density in the top-left panel. The bottom-left image is obtained by adding white noise with a standard deviation of 1 mJy/beam in each simulated channel map, by collapsing the synthetic datacube along the spectral axis, and further convolving with a circular beam of full-width at half-maximum set to $0\farcs05$. Both this noise level and angular resolution are comparable to those currently achieved in ALMA disc gas observations. The bottom-left image shows that the strong asymmetry caused by the planet eccentricity in the disc cavity manifests itself as

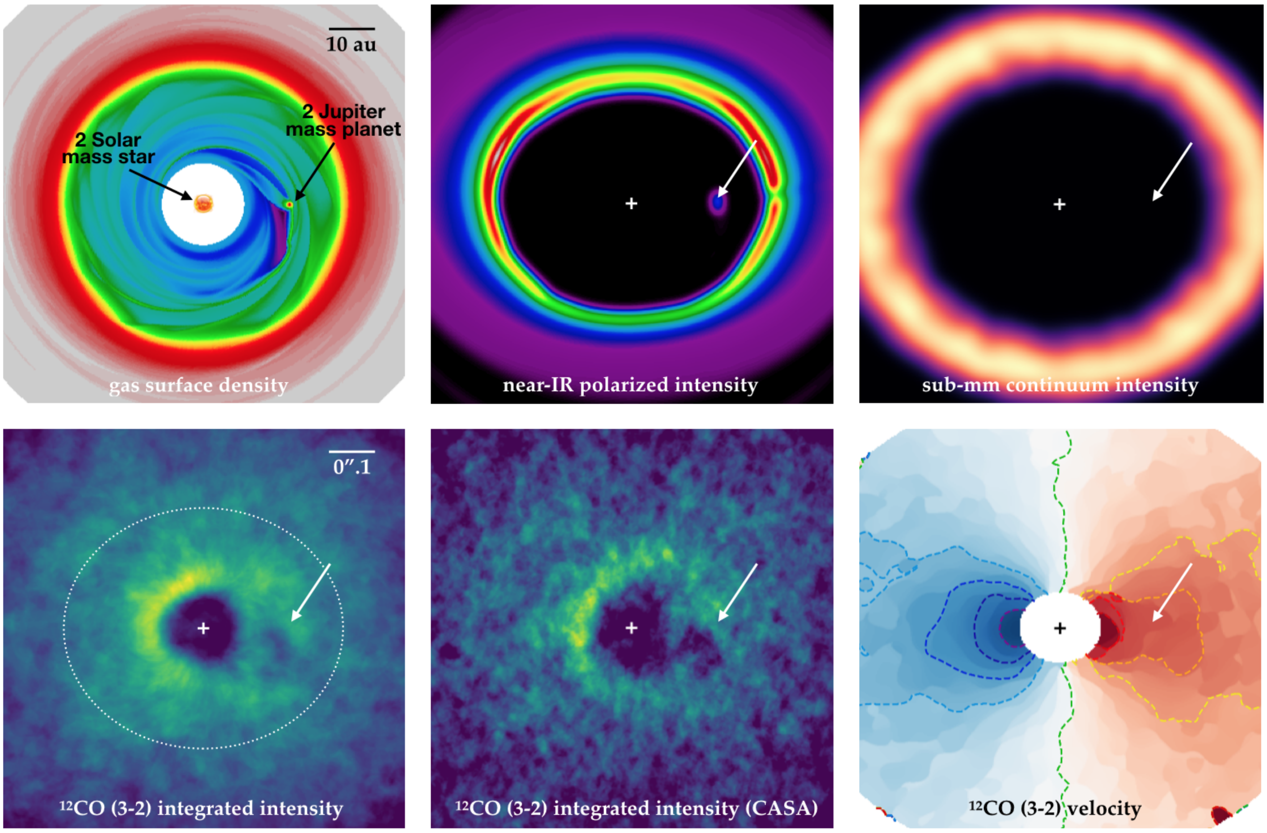

Fig. 2. Summary plot of the results presented in Baruteau et al. (2021). A 2 Jupiter mass planet reaches an eccentricity of about 0.25 after migrating into a ∼30 au wide gas cavity in its protoplanetary disc. Inside the cavity the gas becomes eccentric as well, and the planet gap is no longer annular but features a strongly asymmetric gas surface density (top-left panel). This has two main consequences: (i) the formation of a large-scale asymmetry in the ^{12}CO J=3→2 integrated intensity inside the cavity (bottom-left and bottom-middle panels), and (ii) the distortion of the iso-velocity contours inside the cavity in the ^{12}CO J=3→2 velocity map (bottom-right panel). However, the dust remains mostly outside the cavity on near-circular trajectories, and the dust emission thus shows no significant differences whether the planet is eccentric or still circular inside the cavity. This is illustrated with the polarized intensity at 1.04 μm (top-middle panel) and the dust continuum emission at 0.9 mm (top-right panel). See text for more details about the images. The white arrow spots the planet position in each synthetic image of the disc emission. All panels except the bottom-middle one are adapted from Baruteau et al. (2021).

a large-scale asymmetry in the ^{12}CO J=3→2 integrated intensity, and that this asymmetry could be detected by ALMA.

To strengthen this point, we post-processed the raw output of our gas radiative transfer calculation (synthetic datacube without added noise and beam convolution) with CASA `simalma`, assuming a 5h integration in the `alma.out21.cfg` array configuration, and a precipitable water vapour level of 0.7 mm. This leads to a $0\farcs055 \times 0\farcs043$ beam and a rms noise level (σ) of approximately 1.9 mJy/beam per channel map. Further 2σ clipping was applied to the synthetic data to obtain the final integrated intensity map displayed in the bottom-middle panel in Fig. 2. The image agrees well, overall, with the one obtained with simple white noise. This not only shows that our simple noise model is adequate to produce synthetic emission maps, but it also confirms that the large-scale asymmetry in the ^{12}CO J=3→2 integrated intensity is a feature detectable by ALMA, which could possibly spot the presence of an eccentric Jupiter inside a disc cavity.

The eccentricity of the gas inside the cavity also affects the morphology of the velocity map obtained from the synthetic gas emission. The bottom-right panel in Fig. 2 displays the velocity map for the ^{12}CO J=3→2 line emission at the same time as the other panels in the figure, and the dashed curves show a few iso-velocity contours. The contour levels are chosen symmetrical with respect to the zero line-of-sight velocity, shown in green. Despite the noise, an asymmetry can be clearly seen between contours of positive and negative line-of-sight velocities inside the cavity, which comes about because of the eccentricity of the gas in the cavity. This distortion of the iso-velocity contours constitutes another indirect, detectable signature of the presence of an eccentric Jupiter in a disc cavity.

Our hydrodynamical simulations calculated the orbital evolution of dust particles between 10 μm and 1 cm in size, which are found to quickly escape the disc cavity. Efficient radial drift due to a combination of gas drag and dust turbulent diffusion brings most of these particles near the outer edge of the cavity, which corresponds to a location where the gas pressure has a radial maximum. Around this location, both gas and dust have near-circular orbits, being too distant from the eccentric planet and gas inside the cavity. Consequently, the dust continuum emission in the sub-millimetre basically takes the form of an axisymmetric ring of emission around the edge of the cavity, as shown by the top-right panel of Fig. 2.

For computational reasons, we did not simulate the orbital evolution of dust with a size smaller than 10 μm. The near-infrared polarized intensity image in the top-middle panel in Fig. 2 is actually obtained by assuming that small (sub-micron) dust has the same spatial distribution as the gas *if* the Stokes number remains smaller than a threshold value of 10^{-4} (otherwise, the local dust density is set to 0). This condition is for the dust to be effectively well coupled to the gas: the low gas density inside the cavity implies indeed than even small, micron-sized dust particles have a Stokes number than can reach a few percent, which causes substantial radial drift due to gas drag and turbulent diffusion. With too little small dust expected inside the cavity, the polarized intensity signal mostly arises from outside the cavity, with the notable exception of the circumplanetary environment (spotted by the white arrow in the panel). Both the near-infrared polarized intensity and the sub-millimetre continuum emission show no significant differences whether the planet is eccentric or still circular inside the cavity.

3 Perspectives

In a nutshell, we have shown that the presence of an eccentric planet in a gas cavity could potentially be detected through a large-scale asymmetry in the CO emission inside the cavity. Other aspects of this work that could not fit in this proceeding, like for instance the fact that the optically thick CO emission outside the cavity takes the form of a four-lobed pattern of emission when the disc inclination is larger than about 30°, will be found in Baruteau et al. (2021).

We are currently working on extending this work in several ways. One is by simulating the same physical model in 2D with the multi-fluid hydrodynamical code `Fargo3D`, which has allowed us to include several dust fluids that model the evolution of small, (sub-)micron dust. Dust radiative transfer calculations using the dust density of these several dust fluids as input confirm that the near-infrared polarized intensity displays very little signal inside the cavity, as shown above. Another extension of this work is to simulate the same physical model in 3D. For now, we have been able to perform only one 3D gas-only simulation. It shows eccentricity growth for the planet in quite a similar way as in our 2D simulations, and, interestingly, we also observe the growth of the planet inclination. It will be interesting to investigate how large the inclination of a massive planet could grow as a result of disc-planet interactions in a gas cavity. Another interesting avenue for future work would be to test the predictions of our study to specific protoplanetary discs.

We thank the council members of the French Astronomical Society for keeping our annual meeting organized virtually.

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