Directly observing self-gravitating spiral waves with ALMA

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Abstract

The advent of the Atacama Large Millimeter/submillimeter Array (ALMA) has allowed us to probe down to the midplane of protostellar discs with unprecedented resolution. A surprising result of these observations is that a significant fraction of those systems that have been observed show signs of structure in their discs; rings and spirals may be the norm, rather than the exception. One possibility is that the spiral density waves are being driven by the gravitational instability. Here we present some preliminary results from an analysis that aims to constrain the conditions under which we may be able to directly observe self-gravitating spiral density waves in very young protostellar systems.

Method

Our method is to use semi-analytic modelling to determine the structure of these discs and the distribution of dust grains within these discs (see, for example, Clarke 2009; Rice & Armitage 2009). We then run our model discs through the TORUS radiation transport code (Harries et al. 2004) and then put the resulting emission maps through the ALMA simulator, built into CASA, to determine what would be observed.

We start by assuming the discs settle into a quasi-steady, self-gravitating state with $Q \sim 1$. In such a state, the accretion rate is:

$$\dot{M} = \frac{3\pi\alpha c_s^2 H}{\Omega} \sim \text{constant}$$

where c_s is the sound speed, H is the disc scale height, Ω is the angular frequency, and α is the standard Shakura & Sunyaev (1973) viscosity parameter.

In this quasi-steady, self-gravitating state, we also expect the system to be in a state of thermal equilibrium, with the rate at which energy is generated (via viscous dissipation) being balanced by radiative cooling. We can solve for α, to get

$$\alpha = \frac{4}{9\gamma(\gamma - 1)\beta}$$

where γ is the specific heat ratio, and β is the cooling time, normalised to the local angular frequency. The above, and the $Q \sim 1$, means that – for a given accretion rate - we can self-consistently determine the structure of these discs.

We then impose logarithmic spirals (see Hall et al. 2016) with the dominant mode depending inversely on the disc-to-star mass ratio (i.e., $m \sim 1/q$ – Dong et al. 2015*)* and the amplitude of the spiral depending, locally, on α (i.e., $\delta\Sigma/\Sigma \approx \alpha^{1/2}$ - Cossins et al. 2009; Rice et al. 2011). We also assume that there is a population of solids with sizes that extend from $a_{min} = 0.1$ µm to a_{max}, which we vary from 100 µm to 2000 µm.

The final step is to assume that the grain enhancement, F, in the spirals (as suggested by Rice et al. 2004) depends on the Stokes number, St, through

$$F = G\frac{2d}{St + \frac{1}{St}}$$

where $G = 0.01$ is the non-enhanced grain fraction, and d is an enhancement factor. For Stokes numbers close to unity, we expect the grain fraction to be enhanced by an order of magnitude, or more (Rice et al. 2004; Gibbons et al. 2012).

Grain Fraction.

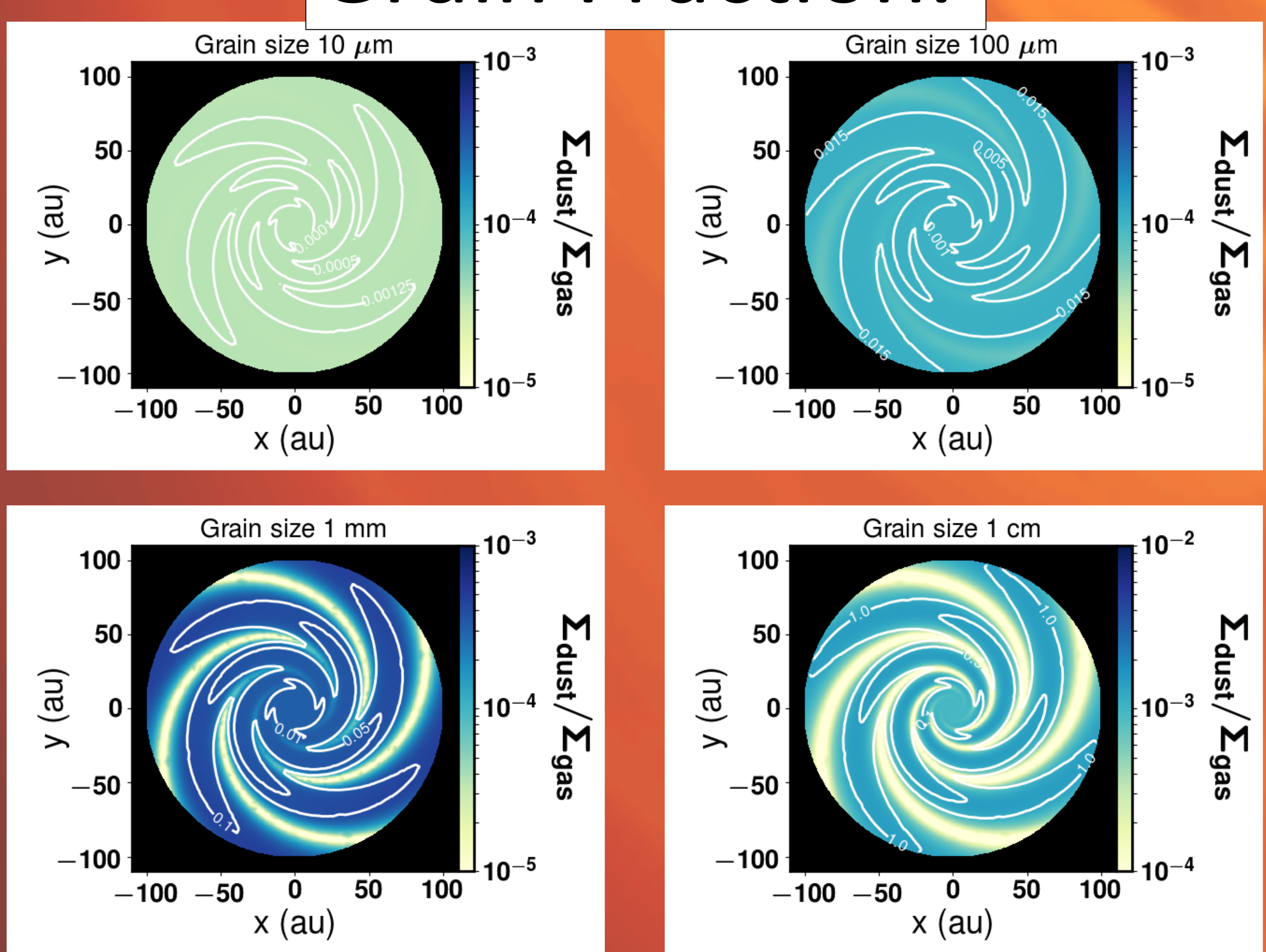

Figure 1: Grain fraction maps for grain sizes of 10µm, 100µm, 1mm and 1cm. For each grain size, it also shows contours of Stokes number. It indicates that there are regions where the Stokes number is ~1 for grain sizes close to ~1cm. The figure also shows the enhanced grain fraction for grain sizes with Stokes numbers close to 1.

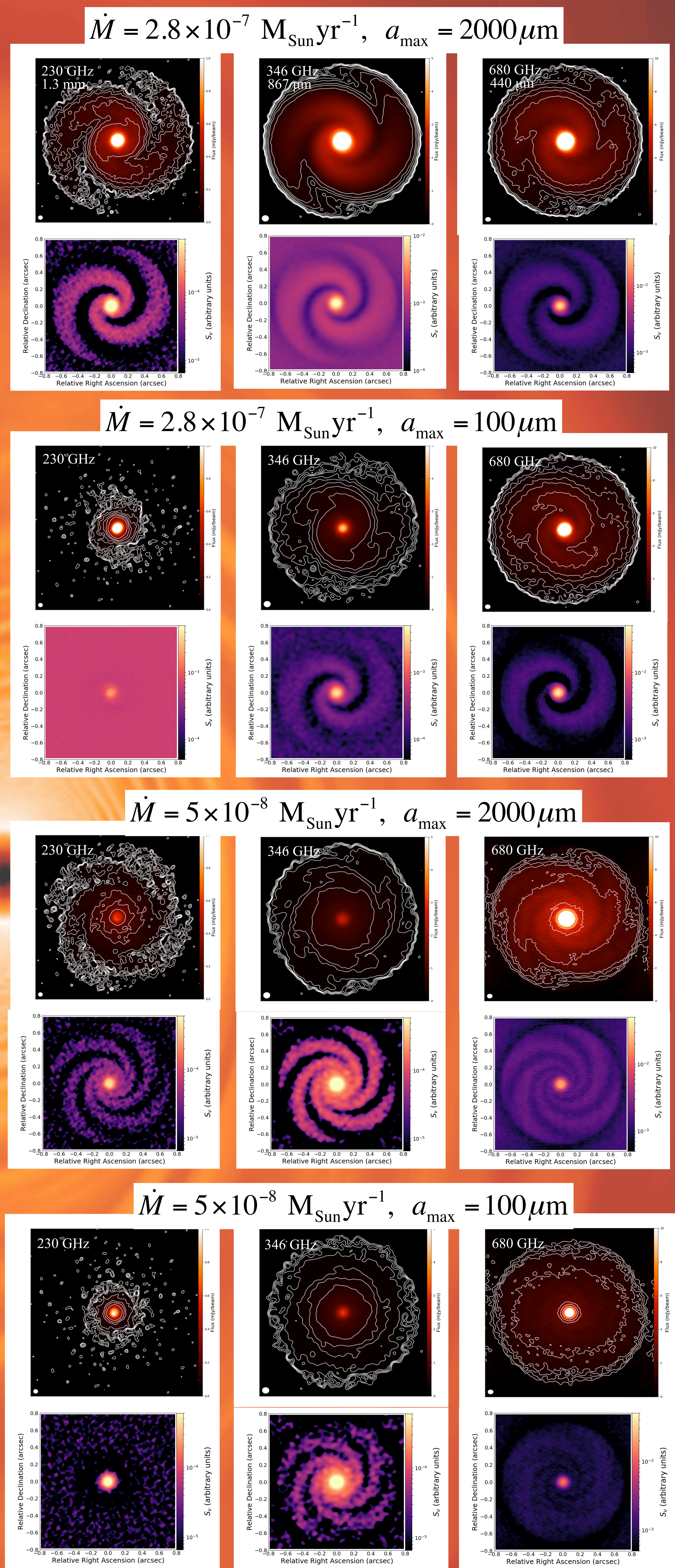

Figure 2: ALMA emission maps, and unsharped masks, for accretion rates of 2.8×10^{-7} M_{sun}/yr and 5×10^{-8} M_{Sun}/yr and for maximum grain sizes of 2000µm and 100µm.

Conclusions:

We present here some preliminary results from an analysis aiming to determine the detectability of self-gravitating spirals waves using ALMA. We conclude that

- Observing self-gravitating spirals requires observing systems that have large disc masses and, hence, that are still very young (< 1 Myr).
- If some grain growth has occurred, the enhancement of solids in the spirals waves can aid the detection of these structures.
- Two-armed, global spirals likely to be present in rapidly accreting systems are more easily detectable than the multi-armed spirals likely to be present in less rapidly accreting systems.
- Using different observing frequencies can help to constrain how much grain has occurred at this epoch; grain growth beyond ~1mm would suggest that these spirals might even be detectable at long wavelengths (230GHz – 1.3mm - or lower).

References*:* Clarke, C.J., 2009, *MNRAS*, **396**, 1066; Cossins, P., et al., 2009, *MNRAS,* **393**, 1157; Dong, R., et al., 2015, *ApJL*, **812**, 32; Gibbons, P., et al., 2012, *MNRAS*, **426**, 1444; Harries, T.J., et al., 2004, *MNRAS,* **350**, 565; Hall, C., et al., 2016, *MNRAS*, **458**, 306; Rice, W.K.M., et al., 2004, *MNRAS,* **355**, 543; Rice, W.K.M. & P.J. Armitage, 2009, *MNRAS,* **396**, 2228; Rice, W.K.M., et al., 2011, *MNRAS*, **418**, 1356; Shakura, N.I. & R.A. Sunyaev, 1973, *A&A*, **24**, 337.