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Tracing Planets in Circumstellar Discs

Observability of Large-scale Disc Structures with ALMA

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Abstract. Planets are assumed to form in circumstellar discs around young stellar objects. The additional gravitational potential of a planet perturbs the disc and leads to characteristic structures, i.e. spiral waves and gaps, in the disc density profile. We perform a large-scale parameter study on the observability of these planet-induced structures in circumstellar discs in the (sub)mm wavelength range for the Atacama Large (Sub)Millimeter Array (ALMA). On the basis of hydrodynamical and magneto-hydrodynamical simulations of star-disc-planet models we calculate the disc temperature structure and (sub)mm images of these systems. These are used to derive simulated ALMA maps. Because appropriate objects are frequent in the Taurus-Auriga region, we focus on a distance of 140 pc and a declination of $\approx 20°$. The explored range of star-disc-planet configurations consists of six hydrodynamical simulations (including magnetic fields and different planet masses), nine disc sizes with outer radii ranging from 9 AU to 225 AU, 15 total disc masses in the range between $2.67 \cdot 10^{-7}\,M_\odot$ and $4.10 \cdot 10^{-2}\,M_\odot$, six different central stars and two different grain size distributions, resulting in 10 000 disc models. At almost all scales and in particular down to a scale of a few AU, ALMA is able to trace disc structures induced by planet-disc interaction or the influence of magnetic fields in the wavelength range between $0.4 \ldots 2.0$ mm. In most cases, the optimum angular resolution is limited by the sensitivity of ALMA. However, within the range of typical masses of protoplanetary discs ($0.1\,M_\odot \ldots 0.001\,M_\odot$) the disc mass has a minor impact on the observability. At the distance of 140 pc it is possible to resolve discs down to $2.67 \cdot 10^{-6}\,M_\odot$ and trace gaps in discs with $2.67 \cdot 10^{-4}\,M_\odot$ with a signal-to-noise ratio greater than three. In general, it is more likely to trace planet-induced gaps in magneto-hydrodynamical disc models, because gaps are wider in the presence of magnetic fields [1]. We also find, that zonal flows resulting from magneto-rotational instability (MRI) create gap-like structures in the disc re-emission radiation which are observable with ALMA. Through the unprecedented resolution and sensitivity of ALMA in the (sub)mm wavelength range the expected detailed observations of planet-disc interaction and global disc structures will deepen our understanding of the planet formation and disc evolution process. This article presents a summary of the study published by [2]

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1 Introduction

Although an early configuration of the Atacama Large (Sub)Millimeter Array (ALMA) became available only recently, its capabilities and its potential for groundbreaking discoveries have already been demonstrated to be enormous [e.g., 3]. Already in the ALMA Cycle 0 configurations its angular resolution and sensitivity were several times higher than those of the Submillimeter Array (SMA). After the completion of the entire array, ALMA will allow one to observe the density structure of young circumstellar discs in unprecedented detail.

Planets are assumed to form in these discs [e.g. 4]. The two main scenarios are core accretion or nucleated instability [e.g. 4] and formation by a gravitational disc instability [e.g. 5]. The additional presence of magnetic fields within the disc influences the planet formation and planet-disc interaction process [e.g. 6–11]. In either case the gravitational potential of a planet perturbs the hosting disc [12, 13], resulting in large-scale structures, such as gaps and spiral density waves [13, 14]. Beyond this, planets are also expected to induce structures in more evolved circumstellar discs (see [15] for a detailed study).

Grid-based hydrodynamical or smoothed particle hydrodynamical (SPH) simulations [16, 17] combined with follow-up radiative transfer simulations [18–24] showed that large-scale disc structures are visible through the continuum re-emission and scattered light of the disc. The case of the observability of simulated line emission were investigated by Semenov et al., Regály et al. and Cleeves et al. in [25–27]. It was found that the intrinsic implementation of the stellar radiation field into the hydrodynamical simulations results in an enlarged vertical extension, particularly of the outer edge of the gap [28]. Furthermore, gaps are enlarged in SPH simulations if compared to the results of grid-based hydrodynamical simulations [23]. Gaps also appear enlarged, if the detachment of larger dust grains from the gas is taken into account [29]. Therefore, we consider non-radiative hydrodynamical simulations as a more conservative disc approximation when evaluating the observability of planet induced gaps. For the infrared wavelength range the observability was explored by Varnière et al., Wolf & D'Angelo and Jang-Condell et al. in [20, 22, 30]. However, due to the much lower optical depth in the (sub)mm regime, observations in this wavelength range are better suited to directly trace the density structure of the disc interior. For high angular resolution observations in this wavelength range large interferometer arrays, like ALMA, are required.

2 Model Setup

Wolf et al. showed that ALMA is indeed able to trace pre-planetary and planet-induced large-scale structures in circumstellar discs [18] and even allows one to observe the circumplanetary accretion region [20]. While most of the earlier studies were mainly focused on exemplary case studies or the impact of high planetary masses [$5 M_{\rm Jup}$, 24], we investigate a large parameter space of stellar, planetary, and disc parameters, to exactly evaluate under which conditions ALMA will allow one to trace characteristic density structures resulting from planet-disc interaction or magneto-rotational instability (MRI) best. Our model setup contains six 3D-hydrodynamical simulations (including magnetic fields and in particular lower planet masses), where gas and dust are homogeneously mixed. Nine disc sizes with outer radii from 9 AU to 225 AU, 15 total disc masses in the range between $2.67 \cdot 10^{-7}\,{\rm M}_\odot$ and $4.10 \cdot 10^{-2}\,{\rm M}_\odot$, four main sequence and two pre-main-sequence stars and two different grain size distributions. Besides this, 14 ALMA configurations, seven observing wavelengths in the range from $330\,\mu$m to 3.3 mm and three exposure times ($\frac{1}{2}$ h, 2 h, 8 h) are considered.

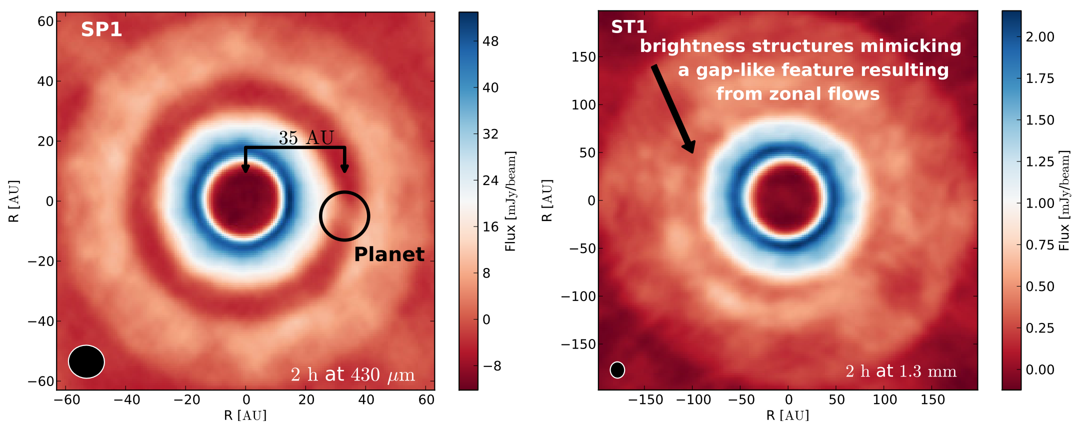

Figure 1. In both figures disc of $M_{\rm disc} = 2.67 \cdot 10^{-2}\,{\rm M}_\odot$ around a Herbig Ae star are shown. Exposure time: 2 h, dust phase: large dust grains. **Left:** Even the circumplanetary region can be detected. (Wavelength: 430 μm, 18$^{\rm th}$ ALMA configuration; inner disc radius: $R_{\rm in}$ = 14 AU, semi-major axis of the planet: $R_{\rm pl}$ = 35 AU, outer disc radius: $R_{\rm out}$ = 63 AU.) **Right:** Observability of brightness structures mimicking gap like features resulting from zonal flows. Wavelength: 1300 μm, 20$^{\rm th}$ ALMA configuration. Credit: Fig. 13 & 16 from Ruge et. al (2012, A&A, accepted, AA/2012/20390) reproduced with permission © ESO.

3 Results

The basic assumptions of this study are typical T Tauri objects at a distance of 140 pc and a declination of $\approx 20°$. For nearly all conceivable parameter combinations large-scale disc structures are detected by ALMA. Even without considering the planet as additional heating source, the circumplanetary high density area is traced (see Fig. 1, left). Gaps are clearly identified if they have a radial extension larger than 2 AU. A higher resolution of the disc structures is limited by the sensitivity and the declination of the source. Nevertheless, ALMA allows to measure gap sizes and therefore to distinguish between planet-to-star ratios or underlying disc models, as both influence the gap size.

Through the observing wavelength range of ALMA large dust particles enhance the feasibility to trace planet-induced disc structures most efficiently. For typical protoplanetary discs the disc mass affects the observability only slightly. In general, a wavelength of 430 μm or 1300 μm in combination with the 14$^{\rm th}$ ALMA configuration ($B_{\rm max} \approx 1600$ m) and an exposure time of two hours is ideal for future surveys aimed at detecting large-scale disc structures. In magneto-hydrodynamical disc models it is more likely to trace planet-induced gaps, because the presence of a magnetic field enlarges the gap size [1]. We find that zonal flow are detectable through a gap like feature with ALMA (see Fig. 1, right). Thus, further multi-wavelength observations are necessary to determine the origin of gaps. Spiral arms created by planet-disc interaction were not traced in our setup. However, comparable structures in self-gravitating discs are predicted to be observable with ALMA [31].

4 Conclusions

We performed a large-scale parameter study of the observability of planet-induced structures in circumstellar discs in the (sub)mm wavelength regime with ALMA. A major fraction of the simulations and summarizing overview charts are available online at http://www1.astrophysik.uni-kiel.de/~placid. For further information see Ruge et al. (accepted by A&A) [2].

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