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Stellar winds can affect gas dynamics in debris disks and create observable belt winds

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ABSTRACT

Context. Gas is now detected in many extrasolar systems around mature stars aged between 10 Myr to $\sim$ 1 Gyr with planetesimal belts. Gas in these mature disks is thought to be released from planetesimals and has been modelled using a viscous disk approach where the gas expands inwards and outwards from the belt where it is produced. Therefore, the gas has so far been assumed to be a circumstellar disk orbiting the star but at low densities, this may not be a good assumption as the gas could be blown out by the stellar wind instead.
Aims. In this paper, we aim to explore when the transition from a gas disk to such a gas wind happens and whether it can be used to determine the stellar wind properties around main-sequence stars that are otherwise hard to measure.
Methods. We developed an analytical model for A to M stars that can follow the evolution of gas outflows and target when the transition occurs between a disk or a wind to finally compare to current observations. The crucial criterion is here the gas density for which gas particles stop being protected from stellar wind protons impacting at high velocities on radial trajectories.
Results. We find that: 1) Belts of radial width ΔR with gas densities $< 7\,(\Delta R/50\,\mathrm{au})^{-1}$ cm^{-3} would create a wind rather than a disk, which would explain the recent outflowing gas detection in NO Lup. 2) The properties of this belt wind can be used to measure stellar wind properties such as their densities and velocities. 3) Very early-type stars can also form gas winds because of the star's radiation pressure rather than stellar wind. 4) Debris disks with low fractional luminosities f are more likely to create gas winds, which could be observed with current facilities.
Conclusions. The systems containing low gas masses such as Fomalhaut or TWA 7 or more generally, debris disks with fractional luminosities $f \lesssim 10^{-5}(L_\star/L_\odot)^{-0.37}$ or stellar luminosity $\gtrsim 20\,L_\odot$ (A0V or earlier) would rather create gas outflows (or belt winds) than gas disks. Gas observed to be outflowing at high velocity in the young system NO Lup could be an example of such belt winds. Future observing predictions in this wind region should account for the stellar wind to be able to detect the gas. The detection of these gas winds is possible with ALMA (CO and CO$^+$ could be good wind tracers) and would allow us to constrain the stellar wind properties of main-sequence stars, which are otherwise difficult to measure (e.g. there are no successful measures around A stars for now).

Key words. Kuiper belt: general – circumstellar matter – Planetary Systems – Solar wind – Sun: Heliosphere – interplanetary medium

1. Introduction

Gas is now detected in most dense planetesimal belts (observed as bright debris disks) around young early-type stars > 10 Myr (Moór et al. 2017). It is now also detected around up to Gyr-old stars (Matrà et al. 2017b; Marino et al. 2017) and around later-type stars, all the way from A-to-M stars (e.g., Marino et al. 2016; Matrà et al. 2019; Kral et al. 2020b; Rebollido et al. 2022), with a remarkable diversity of CO gas masses ranging from 0.1 (e.g. Kóspál et al. 2013; Moór et al. 2017, 2019) to 10^{-7} $M_\oplus$ (Matrà et al. 2017b). The observed CO gas and its daughter products (C and O) are best described as being secondary (Kral et al. 2017, 2019), i.e., the gas is released from planetesimals. It is only for the few most massive systems that a primordial origin (i.e. the hypothesis that the gas would be a remnant of the protoplanetary disk phase) is not completely ruled out. However, there are strong indications that, even for these massive systems, the observed gas is of secondary origin (Hughes et al. 2017; Smirnov-Pinchukov et al. 2021) and CO remains abundant thanks to shielding by carbon naturally produced in a secondary fashion as explained in detail in Kral et al. (2019).

These discoveries have prompted several numerical investigations aimed at understanding the origin and evolution of this long-lived gas component. Up to now, this gas has been modelled as a circumstellar disk orbiting the star and mostly co-located with the planetesimal belts. In these models, the gas production rate has been assumed to be proportional to the dust mass loss rate of the planetesimal belt. This modelling approach was applied to $\sim$ 200 systems and it can explain most observations to date (Kral et al. 2017). Two exceptions to the standard scenario are given by the detection of an atomic gas wind in η Tel in UV (Youngblood et al. 2021) and probably in optical (Rebollido et al. 2018) and also around σ Her in UV (Chen & Jura 2003). The

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