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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 ∼ 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 ∼ 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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central stars being very early (∼A0V), ionised carbon may also become unbound and cannot retain other atomic species through braking Coulomb collisions as is usually assumed (Fernández, Brandeker, & Wu 2006), which is similar to the results of Kral et al. (2017, Fig. 11).

In addition, when recently studying the low gas environment of the Solar System Kuiper Belt (KB), Kral et al. (2021) found that the possible secondary gas released (because of progressive internal warming of large planetesimals) by KBOs (Kuiper belt objects) could be directly blown out by the Solar wind without forming a disk-like structure. Indeed, the likely low gas density in the KB would mean that gas particles are not protected from the Solar wind and each wind proton hitting a gas particle will lead to an ejection (at higher than the local escape velocity) of the gas particle and hence create a gas belt wind. This KBO gas would have a lower density than expected by current viscous gas models and a high velocity heading outwards, characteristic of a wind. Here, the mechanism driving the wind would be stellar wind (SW) and not stellar radiation as presented in the previous paragraph for η Tel. SWs can only affect low gas density systems while radiative winds can impact any gas (that remains optically thin to high energy photons) given that the star is roughly earlier than A0V, which does not apply to many debris disks. The cartoon presented in Fig. 1 shows the classical picture of a gas disk in Keplerian rotation along with the stellar wind and radiative wind mechanisms that become important at low gas densities and high stellar luminosities, respectively.

In this paper, we aim to trace the behaviour of low density gas in presence of SWs and generalize the current models to any circumstellar gaseous system. Our main goal is, in particular, to explore what are the crucial criteria that will determine if the behaviour of a given gas system will be disk-like or wind-like and whether those "belt" winds can be detected by current instruments. To do so, we developed an analytical model to describe the gas density and velocity in low gas mass systems where the effect of SWs can become important. We will also investigate whether these belt winds can be used as proxies to determine the SW properties around main-sequence stars that are otherwise hard to measure (Johnstone et al. 2015a), especially for A stars where no measurements led to a detection so far (Lanz & Catala 1992; Krtička 2014). We will also explore the type of debris disks in terms of fractional luminosity and stellar type that could harbour these belt winds to be able to target them with, e.g., ALMA.

2. The analytical model

We will describe the gas as an idealised one zone model with a scale height H and a constant density throughout for a planetesimal belt located between R and $R + \Delta R$.

The stellar wind velocity around M to A stars is in the range 100-1000 km/s (corresponding to the range of escape velocities at the stellar surface, Johnstone et al. 2015a). After an elastic collision with a wind proton of velocity $v_{\rm SW}$ at an angle ψ (between the proton velocity vector and the normal to the surfaces of proton and gas particle spheres at the point of contact), a gas particle of mean molecular weight μ will have a velocity equals to

$$v_g = \frac{2\cos(\psi) v_{\rm SW}}{\mu + 1} \tag{1}$$

provided that the initial gas particle velocity (commonly of a few km/s along the azimuth) is small compared to the end velocity after impact (see Appendix D to get full expressions). Assuming that the wind velocity is close to the escape velocity at the stellar surface (Johnstone et al. 2015a) then we obtain that a gas particle will become unbound (i.e. with a velocity after impact greater than the local escape velocity) for $R > (\mu + 1)/(2\sqrt{2}\cos(\psi))R_\star$, which we assume in our model. Indeed, for a CO molecule suffering a head-on collision this criterion translates into $R \gtrsim 10 R_\star \sim 0.05$ au, which will be always verified for debris disks (even a worst case scenario of a collision with an impact angle $\psi = 89.5$ deg would imply $R \gtrsim 5$ au, which will also be true as belts are typically located at tens of au).

The model we present here is developed for systems with low gas densities where the mean free path of a wind proton $\lambda_{\rm w}$ crossing the belt is much greater than the belt's width ΔR. This means that a wind proton will at most interact with one gas particle in the disk (see cartoon in Fig. 1 for the basic mechanism). When $\lambda_{\rm w}$ becomes lower than ΔR, much less gas particles can be ejected and the density starts building up to quickly reach the usual steady-state gas disk regime that has been described in the literature up to now (see Appendix C). The main criterion to check whether a system is in the wind regime is thus

$$\lambda_{\rm w} \gg \Delta R. \tag{2}$$

If we rewrite this criterion in terms of the Knudsen number $K_{\rm n} = \lambda_{\rm w}/H$, we obtain that $K_{\rm n} \gg \Delta R/H$, and thus that $K_{\rm n} \gg 1$ because the scale height is much smaller than the belt's width even for the narrowest disks. For such high values of $K_{\rm n}$, gas will not behave like a fluid, and one should use a collisional approach to model the dynamics of the gas rather than standard hydrodynamics as it then behaves as the sum of all individual particles.

The mean free path of a wind proton crossing the gas in the belt can be defined as a function of the gas density $n_{\rm g}$ and its elastic cross-section $\sigma_{\rm col}$ as

$$\lambda_{\rm w} = \frac{1}{n_{\rm g}\sigma_{\rm col}}, \tag{3}$$

where $\sigma_{\rm col} = \pi R_{\rm col}^2$ depends on the particles that are considered to collide with each other. We find that $R_{\rm col}$ depends on the species considered. For an ionised species such as CO^+ or C and O neutral atoms, it is roughly equal to the radius of the species considered, i.e. ∼ 0.78 Å (Miller & Bederson 1978; Olney et al. 1997) or a cross-section of $\sim 2 \times 10^{-20}$ m^2 (see Appendix B). Considering CO, the elastic cross-section with a high-velocity proton is $\sim 2 \times 10^{-18}$ m^2 (Niedner-Schatteburg & Toennies 1992; Dhilip Kumar, Saieswari, & Kumar 2006), which leads to $R_{\rm col} \sim 8$ Å. Solving for Eq. 2 and using Eq. 3 to find the critical gas density $n_{\rm crit}$ below which gas is in the wind regime leads to a gas density

$$n_{\rm g} < n_{\rm crit} = \frac{1}{\Delta R\, \sigma_{\rm col}}, \tag{4}$$

which can be turned into

$$n_{\rm crit} \sim 7\,{\rm cm}^{-3} \left(\frac{\Delta R}{50\,{\rm au}}\right)^{-1} \left(\frac{\alpha_X}{\alpha_{\rm CO}}\right)^{-2/3} \tag{5}$$

where α_X is the polarisability of species X (see Appendix B) and we assumed that $R_{\rm col}$ is in the limit where its radius is fixed by