FREE–FREE EMISSION AND RADIO RECOMBINATION LINES FROM PHOTOEVAPORATING DISKS

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ABSTRACT

Recent infrared observations have demonstrated that photoevaporation driven by high-energy photons from the central star contributes to the dispersal of protoplanetary disks. Here, we show that photoevaporative winds should produce a detectable free–free continuum emission given the range of stellar ionizing photons and X-ray luminosities inferred for young Sun-like stars. We point out that Very Large Array observations of the nearby disk around TW Hya might have already detected this emission at centimeter wavelengths and calculate the wind electron density and mass flow rate. We also estimate the intensities of H radio recombination lines tracing the wind and discuss which ones could be detected with current instrumentation. The detection and profiles of these recombination lines would unambiguously prove our inference of free–free emission from photoevaporating disks like TW Hya. In addition, radio/millimeter data can help constraining wind parameters such as temperature and electron density that are fundamental in measuring mass flow rates.

Key words: circumstellar matter – protoplanetary disks – radio lines: stars – stars: individual (TW Hya)

Online-only material: color figures

1. INTRODUCTION

Photoevaporation driven by high-energy photons from the central star has been long recognized by theorists as a plausible mechanism to speed up the clearing of protoplanetary disks even around low-mass Sun-like stars (e.g., Hollenbach et al. 2000). Recently, we identified a robust diagnostic for photoevaporation in the forbidden [Ne ii] emission line at 12.8 μm (Pascucci & Sterzik 2009). Relatively narrow (≈20 km s$^{-1}$) and slightly blueshifted (a few km s$^{-1}$) [Ne ii] line profiles have been detected toward several evolved disks, including those having a gap in their dust distribution, often called transitional disks (Pascucci & Sterzik 2009; Pascucci et al. 2011; Sacco et al. 2012). Such profiles unambiguously point to unbound gas in a wind. Other wind tracers have been proposed and are being investigated, e.g., the [O i] line at 630 Å (Ercolano & Owen 2010) and the CO rovibrational band at 4.67 μm (Pontoppidan et al. 2011). Because mass flow rates are very sensitive to the density and temperature of the wind, it is necessary to identify additional wind diagnostics to pin down these parameters.

Here, we show that observations at millimeter and radio wavelengths can provide such diagnostics. The photoevaporative wind may be fully (EUV case$^3$) or partially (X-ray case$^4$) ionized and deflections of electrons in the wind by protons should result in continuum free–free emission (Section 2). We point out that Very Large Array (VLA) observations of the nearby disk around TW Hya might have already detected the free–free emission from its photoevaporative wind (Section 3). This emission should be accompanied by H radio recombination lines. We calculate the fluxes of a representative sample of transitions and show that they can be detected with current instruments (Section 5). We conclude by discussing the broader implications of this study (Section 6).

2. FREE–FREE EMISSION FROM IONIZED WINDS

For protoplanetary disks, H$^+$ is the dominant ion in the surface layer ionized by stellar EUV and X-ray photons. In this case the thermal free–free volume emissivity can be fully characterized by a handful of parameters (see, e.g., Padmanabhan 2000):

$$
\epsilon_\nu = 6.8 \times 10^{-38} n_e^2 T^{-1/2} e^{-h\nu/kT} g_{ff} \ [\text{erg cm}^{-3} \text{s}^{-1} \text{Hz}^{-1}],
$$

where $n_e$ is the electron density, $T$ is the gas temperature, and $g_{ff}$ is the velocity-averaged Gaunt factor. This factor depends only on $T$ and the frequency $\nu$ of the observation and can be computed analytically. Converting the emissivity into luminosity ($L_{\nu}$) requires integrating $\epsilon_\nu d\nu$, where $V$ is the volume of the emitting gas. Assuming temperature is constant, $L_{\nu}$ is proportional to the integral of $n_e^2 dV = EM_v$, the volume emission measure.

Assume that the disk surface absorbs a fraction $f$ (≈0.7 for EUV photons, see Hollenbach & Gorti 2009) of the stellar EUV photon luminosity $\Phi_{\text{EUV}}$. In steady state, $f \Phi_{\text{EUV}}$ is equal to the recombination rate of electrons and protons in the ionized gas, and the latter is proportional to $EM_v$. Therefore, the free–free luminosity is linearly dependent on the EUV photon luminosity. Similarly, the absorbed X-rays create a hydrogen ionization rate balanced by recombinations, so that the free–free emission caused by X-ray ionizations is linearly proportional to the locally incident X-ray photon luminosity. Here we use the fact that, including secondary ionizations, X-ray ionization rates (in s$^{-1}$) are equal to the incident X-ray luminosity divided by 40 eV, the mean energy required for a single ionization (Glassgold et al. 2004). Because X-rays penetrate deeper in the disk than EUV photons, the fraction $f$ of photons absorbed by the disk is lower. Detailed modeling suggests a value of 0.5 for a ~5000 K gas (Gorti et al. 2011). Assuming the EUV ionized layer has $T = 10,000$ K and the X-ray layer has $T = 5000$ K, the free–free flux density at 3.5 cm can be written as

$$
F_{3.5 \text{ cm}} = 2.9 \times 10^{-39} \left( \frac{51}{d} \right)^2 \Phi_{\text{EUV}} \ [\mu \text{Jy}]
$$

(2)

$$
F_{X} = 2.4 \times 10^{-29} \left( \frac{51}{d} \right)^2 L_X \ [\mu \text{Jy}],
$$

(3)

where $d$ is the source distance in pc (where 51 pc is the distance of TW Hya; Mamajek 2005), $\Phi_{\text{EUV}}$ is measured in photons...
per second, and $L_X$ in erg s$^{-1}$. We note that the bulk of the X-ray-heated gas is typically at $\sim 1000$–$2000$ K. However, the free–free flux density decreases with gas temperature such that $F_{3.5\,\text{cm}}$(1000 K) $< 0.5 \times F_{3.5\,\text{cm}}$(5000 K).

Direct measurements of $\Phi_{EUV}$ from young stars are not available because EUV photons are easily absorbed by H in the interstellar medium (ISM). Alexander et al. (2005) used emission lines at FUV wavelengths to derive order-of-magnitude estimates of $\Phi_{EUV}$ for five young solar mass stars of $10^{41}$–$10^{44}$ s$^{-1}$. Based on this large range, we can expect to detect a free–free 3.5 cm flux from the fully ionized layer ranging from 290 $\mu$Jy to 0.3 Jy at the distance of TW Hya. Stellar X-ray luminosities have been measured in several star-forming regions. The XMM survey of Taurus finds $L_X$ values from $10^{50}$ to $10^{51}$ erg s$^{-1}$ for solar-mass stars (Güdel et al. 2007) which convert into a free–free flux from 2.4 to 240 $\mu$Jy at 3.5 cm in a few hours of integration, this simple calculation illustrates that free–free emission from a fully or partially ionized disk surface can be detected with current instrumentation out to the distance of nearby star-forming regions like Taurus.

3. THE CASE OF TW Hya

TW Hya is a nearby, relatively old star surrounded by a transitional disk (e.g., Calvet et al. 2002). The exact structure and extension of the dust gap is debated (Akeson et al. 2011 for a discussion) as well as the mechanisms responsible for the inner clearing (e.g., Gorti et al. 2011).

Recently, we found that the disk of TW Hya is dispersing gas from its surface via photoevaporation driven by high-energy photons from the central star (Pascucci & Sterzik 2009). The photoevaporative wind, as traced by the [Ne ii] line at 12.81 $\mu$m, originates beyond the radius that marks the transition between the thin and thick dust disks, regardless of whether that occurs at 1 or 4 AU, and extends out to about 10 AU (Pascucci et al. 2011).

Having evidence for a fully or partially ionized disk layer and given its proximity, TW Hya is the ideal source to search for the type of free–free emission discussed in Section 2. Figure 1 shows the long-wavelength portion of the source spectral energy distribution (SED) covering from 0.87 mm out to 6 cm (data are from Wilner et al. 2005; Andrews et al. 2012 and references therein). Emission from most disk grains at these long wavelengths is optically thin, hence the flux depends on the wavelength as $F_\nu \propto \lambda^{(2+\beta)}$, where $\beta$ is the wavelength dependence of the dust opacity. In the log–log plot shown in Figure 1 the best fit to the millimeter data (0.87 to 3.4 mm) is for an SED slope of 2.57 $\pm$ 0.06, implying a $\beta$ of 0.6. This $\beta$ is typical of classical and more evolved disks in the Taurus–Aquarius star-forming region (Ricci et al. 2010). Our fit fully accounts for the observed 7 mm flux but it is lower than the $3.5\,\text{cm}$ flux by more than a factor of two. The extra emission at 3.5 cm amounts to $140 \pm 40 \,\mu$Jy.

A fully ionized wind by (4–6) x $10^{40}$ EUV photons per second or a wind partially ionized by a star with $L_X$ of (4–8) x $10^{39}$ erg s$^{-1}$ can alone account for this excess emission (see Equations (2) and (3)). The X-ray luminosity of TW Hya is measured to be $\sim 1.5 \times 10^{30}$ erg s$^{-1}$ (Brickhouse et al. 2010) meaning that X-rays contribute to only $\sim 35 \,\mu$Jy of the excess flux, even in the optimistic assumption that all the X-ray-heated gas is at 5000 K. This small flux is within the 1$\sigma$ flux uncertainty, hence most of the measured excess emission at 3.5 cm must arise from the fully ionized EUV layer in this disk.

The $\Phi_{EUV}$ derived from Equation (2) converts into a mass loss rate $\dot{M}_{\text{wind}}$ of (2–5) x $10^{-10}$ $M_\odot$ yr$^{-1}$ (Hollenbach et al. 1994). The mass accretion rate of TW Hya is time variable and literature values span a large range, from close to the inferred $\dot{M}_{\text{wind}}$ (5 x $10^{-10}$ $M_\odot$ yr$^{-1}$; Muzerolle et al. 2000) to more than 10 times higher (Alencar & Batalha 2002; Dupree et al. 2012). This range suggests that EUV-driven photoevaporation does not dominate yet over viscous accretion. We note that indirect measurements of $\Phi_{EUV}$ for TW Hya, including from the [Ne ii] line, range from (2–5) x $10^{41}$ s$^{-1}$ with a large uncertainty of about a factor of five (Herczeg 2007; Pascucci & Sterzik 2009). Our estimates from the free–free continuum emission are consistent with these values within the reported error bars.

The wind electron density $n_e$ can be also estimated from the free–free luminosity and $E_{\text{UV}}$. Hollenbach & Gorti (2009) found that for disks EUV illuminated by the central star most of $E_{\text{UV}}$ comes from regions near the “gravitational radius” $r_g$, where the hydrogen thermal speed is equal to the escape speed from the star gravitational field. This is indeed what we see in the [Ne ii] line, whose critical density is above the wind density: $r_g$ is 6.2 AU for TW Hya and most of the [Ne ii] emission arises within a radius of 10 AU (Pascucci et al. 2011). Additionally at the gravitational radius we have a vertical extent $z_{\text{HII}} \sim r_g$ (Hollenbach & Gorti 2009). Based on these considerations, we adopt $r_{\text{HII}} = 10$ AU and $z_{\text{HII}} = 5$ AU and find $n_e \sim 10^5$ cm$^{-3}$.

4. RADIO CONTINUUM EMISSION FROM OTHER MECHANISMS

We briefly examine five additional mechanisms that could produce excess emission at centimeter wavelengths and discuss what observations are needed to discriminate among them. Collimated ionized outflows/jets from Class I and II sources present flat or positive spectral indices ($\alpha \geq -0.1$ with $F_\nu \propto \nu^\alpha$)

![Figure 1. SED of the TW Hya disk from 0.87 mm out to 6 cm. Observed fluxes (empty circles) and 3$\sigma$ upper limits (downward triangle) are from Wilner et al. (2005) and Andrews et al. (2012). The dashed line is a linear fit to the millimeter fluxes between 0.87 and 3.4 mm. Note that this fit fully accounts for the 7 mm flux but underpredicts the 3.5 cm flux by a factor of 2.2. Dotted lines are free–free emission relations expected for optically thin (\(\sigma = 0.1\)) and thick (\(\sigma = 0.4\)) gas passing through the observed minus dust emission at 3.5 cm. We also plot literature 3.5 cm fluxes from Class I (Anglada et al. 1998) and Class II/classical disks (Rodmann et al. 2006) scaled at the distance of TW Hya.](image)
at radio wavelengths pointing to free–free emission (e.g., Anglada et al. 1998; Rodmann et al. 2006 and Figure 1). Hence, searches for free–free emission from photoevaporative winds should be carried out in evolved systems like TW Hya that have no jets/outflows detected in molecular, atomic, and/or ionic tracers (Alencar & Batalha 2002; Pascucci et al. 2011). Most transitional disks belong to this category. We can estimate the jet contribution to the free–free emission by using the empirical relation between momentum rate in the molecular outflow and the radio continuum luminosity (Equation (3) from Anglada et al. 1998). For TW Hya, even the largest measured mass accretion rate and ratio between outflow and accretion (Hartigan et al. 1995; White & Hillenbrand 2004) would produce a 3.5 cm free–free flux of only ~30 μJy for a typical jet velocity of 200 km s\(^{-1}\), ~20% of the measured excess flux. Similarly, any free–free contribution from accretion shocks near the forming star is reduced for evolved disks. In the case of TW Hya, it should amount to less than a few μJy at 3.5 cm based on the calculations of Neufeld & Hollenbach (1996).

Another source of radio emission in young stars is non-thermal emission originating in magnetic fields, also known as gyrosynchrotron radiation. A few protostars (Class0/I) have been reported to have this type of emission based on spectral indices α < −0.1 and about an order of magnitude variability, presumably due to magnetically induced flares (e.g., Forbrich et al. 2011). The easiest way to discriminate between free–free and gyrosynchrotron radiation is by obtaining radio observations at multiple wavelengths and computing the radio spectral index. In the case of TW Hya, where the only radio detection is at 3.5 cm, time monitoring can rule out gyrosynchrotron emission (Wilner et al. 2005).

Finally, both very large (millimeter-size) and very small (nanometer-size) grains can enhance the centimeter flux. In the case of TW Hya, Wilner et al. (2005) showed that a population of 5–7 mm sized grains, containing 99.9% of the dust mass, can match the 3.5 cm excess emission. The remaining 0.1% of the dust mass is in grains of sizes between 0.005 and 1 μm in their model suggesting a strictly bimodal dust distribution. At the other end of the grain size spectrum, Rafikov et al. (2006) showed that nanometer-sized grains spinning at thermal rates can produce detectable electric dipole emission at λ ≥ 0.6 cm. This emission has a characteristic bell-like spectral shape which can be easily distinguished from the power-law spectra of free–free and synchrotron emission.

As discussed in Section 5, free–free thermal emission from photoevaporating disks is optically thin at millimeter and centimeter wavelengths, meaning a radio spectral index α (for the gas only) of −0.1. Thus, the combination of sensitive EVLA continuum observations at 3.5 and 6 cm is the most straightforward way to constrain the radio slope of evolved disks and discriminate among the different mechanisms discussed here. However, the most direct way to test our inference of free–free emission from photoevaporating disks is via the detection of H recombination lines and associated blueshifts.

5. HYDROGEN RADIO RECOMBINATION LINES

In a region that is fully or partially ionized, electrons will be captured by protons to a state n and undergo transitions to lower levels. We compute here the intensities of a representative sample of H\(\alpha\) recombination lines at millimeter and radio wavelengths as a function of \(\Phi_{\text{EUV}}\) and \(L_X\).

In our calculation, we consider spontaneous and internally stimulated emission (masing) but neglect externally stimulated emission. The line flux density \(F_l\) can be written as

\[
F_l = B_\nu(T)\Omega_{\text{H}2} \left\{ \frac{b_n\tau^*_n + \tau_c}{\tau^*_n + \tau_c} \left(1 - e^{-(\tau^*_n + \tau_c)}\right) - \left(1 - e^{-\tau_c}\right) \right\}
\]

where \(B_\nu(T)\) is the Planck function at the gas temperature \(T\); \(\Omega_{\text{H}2}\) is the solid angle subtended by the ionized wind; \(b_n\) is the LTE departure coefficient for the upper state \(n\); and \(\tau_n\), \(\tau^*_n\), and \(\tau_c\) are the continuum and line optical depths (the latter corrected for non-LTE effects) at the specific frequency \(\nu_l\) (Bell & Seaquist 1978). For the LTE departure coefficients we refer to Salem & Brocklehurst (1979) for transitions \(n ≥ 50\) and to Walmsley (1990) for lower \(n\), i.e., for lines that fall at millimeter wavelengths.

Equation (4) simplifies greatly for the photoevaporative winds discussed in Section 2 because we find line and continuum optical depths that are \(\ll 1\) at millimeter and radio wavelengths. This also means that any masing is not significant because of the relatively low electron densities and path lengths. To corroborate this statement let us consider the so-called turnover wavelength \(\lambda_T\), the wavelength at which \(\tau_c = 1:\lambda_T \sim 100/(T^{−1.35}n_e^{2.2}Z_{\text{HII}})^{0.5}\), where all units are in cgs except for \(Z_{\text{HII}}\), which is in pc. One sees that even a partially ionized wind at 5000 K becomes optically thick at wavelengths >20 cm for plausible wind values (Section 2). Hence, we can use the optically thin approximation to re-write Equation (4) as:

\[
F_l = B_\nu(T)\Omega_{\text{H}2} b_n\tau^*_n
\]

The line optical depth can be written as \(\tau^*_n = \tau_n r^*\), hence \(F_l = F_{cr} r^* b_n\) where \(F_{cr}\) is the thermal continuum flux. Here, \(r^*\) is the line-to-thermal continuum ratio in LTE at line center assuming thermal broadening of the line:

\[
r^* = 2.33 \times 10^8 \Delta\nu^{-1} \nu_{l}^{2.1} T^{-1.15} E_l/E_c
\]

(\(\nu_l\) in GHz, \(T\) in K) with \(\Delta\nu\) being the line width\(^5\) in kHz, and \(E_l/E_c\) the ratio of line to continuum emission measure which we assume to be 0.9 following Bell & Seaquist (1978). Because \(F_{cr}\) is proportional to \(\Phi_{\text{EUV}}\) and \(L_X\) (Section 2) we obtain the following relations for the line flux densities assuming the Rayleigh Jeans approximation (which is valid for this hot gas even at millimeter wavelengths):

\[
F_l = 2.1 \times 10^{-41} \nu_l b_n \left(\frac{51}{d}\right)^2 \Phi_{\text{EUV}} (\mu\text{Jy})
\]

\[
F_l = 5.4 \times 10^{-31} \nu_l b_n \left(\frac{51}{d}\right)^2 L_X (\mu\text{Jy}),
\]

where \(\nu_l\) is in GHz and \(d\) is the distance in pc.

The upper panel of Figure 2 shows flux densities for a representative set of H\(\alpha\) recombination lines for a fully ionized EUV wind (10,000 K gas) and a partially ionized X-ray wind (5000 K gas). We have taken \(\Phi_{\text{EUV}} = 10^{41} \text{ s}^{-1}\) and \(L_X = 10^{30} \text{ erg s}^{-1}\), respectively, and scaled the fluxes to 51 pc. Line-to-free–free continuum ratios are shown in the panel below. They scale with the gas temperature as \(\sim T^{-1.65}\), which explains why the cooler X-ray gas has higher line-to-free–free-continuum ratios. These ratios also increase as \(\nu_{l} r^* b_n\) (with \(b_n\) slowly decreasing) as we move to high frequencies/short wavelengths, suggesting that millimetric transitions might be the easiest to detect. However, the dust thermal emission increases...
more steeply at shorter wavelengths as illustrated in the lower panel of Figure 2, reducing the total line-to-continuum ratio. For the dust contribution, we have taken here the mean 7 mm profile of Hα recombination lines at centimeter and millimeter wavelengths. The EVLA could detect (but not spectrally resolve) some of these lines given the sensitivity of ~5 μJy rms in about 3 hr with a bandwidth of ~500 MHz. In the millimeter regime, we will be able to detect Hα recombination lines only if the dust disk emission is spatially more extended than the free–free emission, so that the line-to-continuum ratio can be increased at r_{rg}, where the wind emission peaks. Evolved disks with dust gaps and large Φ_{EUV} (or L_X) are the best candidates to detect H recombination lines at millimeter wavelengths.

6. CONCLUSIONS AND PERSPECTIVES

This Letter investigates the radio/millimeter properties of photoevaporative winds driven by high-energy photons from the central star. We show that free–free continuum emission from fully (EUV case) or partially ionized (X-ray case) winds is directly proportional to the stellar ionizing flux/X-ray luminosity. Given the inferred/measured Φ_{EUV}/L_X of young Sun-like stars, centimeter wind emission should be detectable out to nearby star-forming regions. Other mechanisms producing centimeter emission can be ruled out with observations at multiple wavelengths measuring the radio spectral slope. However, the smoking gun for free–free emission from photoevaporative winds would come from the detection and profiles of H radio recombination lines. Our calculations suggest that a few of them should be detectable at radio wavelengths and might be also detectable in the millimeter with ALMA if the dust contribution can be spatially resolved out using high resolution.

We point out that VLA observations might have already detected the free–free continuum emission from the nearby and photoevaporating disk of TW Hya. Taking TW Hya as a case study, we show how radio observations can be used to infer the ionizing luminosity reaching the disk, the wind temperature, and the electron density, and hence compute mass flow rates from star-driven photoevaporation. This latter parameter is essential to estimate disk lifetimes and understand whether photoevaporation is primarily driven by stellar X-rays at 10^{-8} M_⊙ yr^{-1} (e.g., Ercolano & Owen 2010) or by EUV photons at a rate about a hundred times lower (e.g., Alexander et al. 2006). Evolved disks with low-mass accretion rates should be the prime targets to expand the analysis presented here and to identify the typical mass loss rates from star-driven photoevaporation. These empirically derived rates will enable the evaluation of the impact of photoevaporation on the dispersal of protoplanetary disks, as well as on planet formation and migration.

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Facilities: VLA, ALMA

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