YOUNG CIRCUMSTELLAR DISKS NEAR EVOLVED MASSIVE STARS AND SUPERNOVAE

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ABSTRACT

There is increasing evidence that low-mass stars with circumstellar disks can be born close to massive stars, in some cases within tenths of a parsec. If the disks have lifetimes greater than those of the more massive stars, they are exposed to radiation fields and gas flows from the late evolutionary phases and supernovae of the massive stars. The fast flows from supernovae are likely to give some stripping of mass from the disks but do not typically lead to complete disruption of the disks. In the slow wind from a red supergiant star, there is the possibility of gravitational accretion of wind matter onto the circumstellar disk. In the supernova explosion of a red supergiant, the radiative flux at the time of shock breakout can heat and ionize a nearby disk, leading to transient, narrow-line emission. There are consequences for the solar nebula if it was born ~0.2 pc from a massive star that became a red supergiant. Accretion from the wind could supply a substantial amount of $^{26}\text{Al}$ to the disk. The high radiative luminosity of the eventual supernova could lead to the melting of dust grains and the formation of chondrules. The passage of the supernova ejecta could drive a shock wave in the disk, heating it.

Subject headings: circumstellar matter --- solar system: formation

1. INTRODUCTION

There is growing evidence that low-mass stars form in association with massive stars. Infrared studies of Orion show evidence for a cluster of about 2000 low-mass stars within 2 pc of the Trapezium; the core radius of the cluster is ~0.2 pc (Hillenbrand & Hartmann 1998). Stars in Orion within 0.3 pc of the central star $\theta^1$ C Ori show observable disks because of the effects of photoionization by the massive star (O’Dell, Wen, & Hu 1993). The disk ages may be limited by mass loss driven by a photodissociation front (Störzer & Hollenbach 1999). However, the age of the association of ~10$^6$ yr and the fact that disks are apparently present within ~0.01 pc of $\theta^1$ C Ori shows that the disks can survive, perhaps because their host stars are on radial orbits (Störzer & Hollenbach 1999). Absorption studies of π Sco in the upper Sco association give evidence for a population of circumstellar disks that have properties like those in Orion (Bertoldi & Jenkins 1992). The estimated age of the upper Sco association is $5 \times 10^6$ yr for both low- and high-mass stars, with a small age dispersion (de Geus 1992; Preibisch & Zinnecker 1999). De Geus (1992) presents evidence that a supernova occurred in the association (1–1.5) $\times 10^6$ yr ago; it is possible that these circumstellar disks have been exposed to a nearby supernova.

There have been estimates of the lifetime of the solar nebula ~10$^6$ yr, but Podosek & Cassen (1994) argue that a lifetime ~10$^7$ yr or more is plausible. These longer lifetimes, together with evidence for clusters of low-mass pre–main-sequence stars near massive stars, suggest that many gaseous disks may be exposed to the late evolutionary phases and supernovae of massive stars. The lifetime of a 60 $M_\odot$ (initial mass), or 05 main-sequence, star is ~4 $\times 10^7$ yr and that of a 20 $M_\odot$ (O9) star is ~1 $\times 10^7$ yr. In their late phases, these stars go through a red supergiant and/or a Wolf-Rayet phase, with strong stellar winds. They end their lives as supernovae.

In view of the fact that many circumstellar disks may be exposed to these unusual environments, the aim of this Letter is to investigate their effects on the disks. This is of interest both for possible observational consequences of the disks and for possible implications for the early solar system, if it went through such a phase. The effects of radiation on disks and of flows past a disk are discussed in §§ 2 and 3, respectively. The possible implications for the early solar system are discussed in § 4.

2. EFFECTS OF RADIATION

The effects of a main-sequence stellar radiation field on a disk have been treated in detail for the case of Orion. Störzer & Hollenbach (1999) find that the far-ultraviolet stellar flux determines the mass loss through a photodissociation front. In this regime the mass-loss rate does not have a strong dependence on the stellar radiation flux. However, once the radiation flux drops below the flux at which the far-ultraviolet emission dominates, the extreme ultraviolet emission dominates and the mass-loss rate drops as the square root of the stellar flux. For the case of $\theta^1$ C Ori, Störzer & Hollenbach (1999) estimate that the transition occurs at a distance of ~0.3 pc from the O star, which is the outer limit at which disks are observed. The rate of ionizing photon production, $S$, from $\theta^1$ C Ori is ~$2.6 \times 10^{48}$ s$^{-1}$, within the range $2 \times 10^{48}–8 \times 10^{49}$ s$^{-1}$ for O9 to O4 main-sequence stars (Panagia 1973). The Orion case may thus be typical of expectations around an O star.

Similar conditions are relevant to the case of Wolf-Rayet stars, if that is the next phase of evolution of the massive star. The case of $\gamma^2$ Velorum is of interest because it is the brightest Wolf-Rayet star, and X-ray observations show evidence for a surrounding cluster of pre–main-sequence stars (Pozzo et al. 2000). There is no evidence at present for disks around these stars, the presence of which would be important for establishing disk lifetimes. For a distance of 410 pc, these stars extend to a radial distance from $\gamma^2$ Velorum of 2 pc; $\gamma^2$ Velorum is a WC8 star in a binary system with an O9 I star (Conti & Smith 1972). The ultraviolet radiation field is dominated by the O9 I star, which has $S \approx 1.3 \times 10^{49}$ s$^{-1}$ (Panagia 1973). Although this is comparable to the case of $\theta^1$ C Ori, the stronger wind expected for the Wolf-Rayet star could affect the appearance of nebulae around disks (see § 3).

When the massive star becomes a supernova, the highest luminosity occurs when the shock front breaks out of the stellar surface and there is a burst of hard radiation. In the case of a red supergiant progenitor, ~$2 \times 10^{48}$ ergs of hard ultraviolet/
soft X-radiation is emitted over $10^3$ s (Klein & Chevalier 1978; Matzner & McKee 1999). For a Type Ib or Ic supernova from a Wolf-Rayet star, the smaller surface area leads to $3 \times 10^{44} - 2 \times 10^{46}$ ergs of soft X-radiation emitted over 2–20 s (Matzner & McKee 1999). The case of the unusual supernova SN 1987A is intermediate between these. The initial burst can be followed by prolonged X-ray emission if the shock wave runs into a dense circumstellar wind.

The supernova radiation can heat and ionize gas in the disk, leading to a delayed burst of line radiation. I consider a disk with mass $M_d = 0.01 M_{\odot}$ and radius $d = 10^{15} d_{15}$ cm, so that the typical surface density is $\sigma_d = M_d/(\pi d^2) = 6.4 M_d d^{-2} \, d_{15}^{-3}$ g cm$^{-2}$. The disk scale height at a radius $d$ is $H \approx 0.7 \times 10^{12} d_{15}^{1/2} T_2^{1/2} (M_d/M_{\odot})^{-1/2}$ cm, where $T$ is the temperature of the disk in units of $10^5$ K and $M_d$ is the mass of the host star, so that the typical density in the disk is $\rho_d \approx 1 \times 10^{-15} d_{15}^{2/7} T_2^{-1/2} M_d^{-1} (M_d/M_{\odot})^{1/2}$ g cm$^{-3}$. For the explosion of a red supergiant with a $2 \times 10^4$ ergs initial burst of radiation, the amount of radiative energy intercepted by a disk is $1 \times 10^{42} (r/0.2 \, \text{pc})^{-2}$ ergs, where $r$ is the distance of the disk from the massive star. At $r = 0.2$ pc, the supernova radiation is absorbed in the outer layers of the disk and reradiated; a layer $0.7 \times 10^{14}$ cm thick can be ionized at an H density of $n_H = 2 \times 10^4$ cm$^{-3}$. If present, dust grains would compete with gas for the ionizing photons, but they are likely to be evaporated by the high luminosity (see below). Based on calculations by Chevalier & Fransson (1994), I estimate that several percent of the reradiated luminosity is in the H$\alpha$ line. The timescale for the emission at high density is determined by the light travel time, $\tau \approx 10^3$ s, leading to an H$\alpha$ luminosity of $6 \times 10^{46} (r/0.2 \, \text{pc})^{-2}$ ergs s$^{-1}$, which could be observed up to 1.3$(r/0.2 \, \text{pc}) \, \text{yr}$ after the initial explosion.

Although this emission is faint compared to the supernova luminosity, there is some chance of detection because it is in a narrow line. The case we have been able to observe in most detail is SN 1987A, which apparently had a progenitor $20 M_{\odot}$ progenitor star with a lifetime of $1 \times 10^7$ yr (Arnett et al. 1989). This is close to the age limit at which substantial disks are expected to be present. Efremov (1991) finds that the supernova is at the edge of a star cluster with the expected age, but it is sparse (see also Panagia et al. 2000). A number of short-lived, discrete sources of H$\alpha$ emission were observed near the supernova in the first 2 yr after the explosion (Cumming & Meikle 1993 and references therein). Although its parameters ($d \approx 2 \times 10^{15} \, \text{cm}$ and $r \approx 0.5 \, \text{pc}$) are reasonable for a circumstellar disk, the best observed emission knot (Cumming & Meikle 1993) appears unlikely to be a disk because of the 11 km s$^{-1}$ redshift of the narrow H$\alpha$ line compared to the centroid of the bright ring emission. Cumming & Meikle (1993) estimate a density of $(1-2) \times 10^4$ cm$^{-3}$ from the 60 day timescale of the emission; this is low for a circumstellar disk, but it may be that only the surrounding, low-density parts of the disk were heated and ionized. SN 1987A was a compact and relatively low luminosity supernova, so dust should survive at this distance from the supernova; but the dust opacity through the ionized region is not expected to be large. Cumming & Meikle (1993) find that the energy in the H$\alpha$ line was consistent with the expected ionizing radiation from the supernova.

The supernova radiation can process dust in the disk (by vaporization and melting), and the surviving dust can emit scattered light as well as reradiate infrared light from absorbed supernova radiation. Vaporization is caused by the highest luminosity radiation that is absorbed by dust. From the results of Dwek (1983) for $n = 1$, where the dust opacity is $\kappa \propto \lambda^{-\alpha}$, and an evaporation temperature of $T_e = 1500$ K, the dust is evaporated out to $r \approx 0.3 L_{15}^{1/2}$ pc from the supernova, where $L_{15}$ is the luminosity in units of $10^{45}$ ergs s$^{-1}$. For a red supergiant explosion, the initial ionizing burst has $L_{15} \approx 2$, so that a disk at $r = 0.2$ pc has its dust within the ionized region evaporated. The luminosity rapidly drops, so a layer just interior to the evaporated region is expected to have its dust melted. The properties of this layer depend on the disk position and the grain properties.

Dust in circumstellar disks can reprocess the nonionizing supernova light, which typically has a total energy $\sim 2 \times 10^{47}$ ergs and $L_{15} < 0.01$ for a Type II supernova, to scattered and reradiated infrared light. The problem with detecting this emission is that it is not transient and is likely to be difficult to distinguish from dust emission from the presupernova wind (Dwek 1983). The disks are optically thick to the supernova light, so the fraction of the supernova radiative energy that is reprocessed depends on the area covering factor of circumstellar disks. As a result of the initial dust evaporation, the massive star wind is likely to be optically thin to the supernova light, but it has a 100% covering factor.

### 3. EFFECTS OF FLOWS

In addition to strong radiation fields, the environment of an evolved massive star can have flows that affect a nearby circumstellar disk. In the case of main-sequence stars, the properties of the cometary nebulae observed around disks in Orion can be explained by the effects of radiation from the massive star (e.g., McCollough et al. 1995; Störzer & Hollenbach 1999). Although there is evidence for a stand-off bow shock in the wind from $\theta^1$ C Ori in some cases (McCollough et al. 1995), the wind does not play a role in driving mass loss from the disks. The mass-loss rate from Wolf-Rayet stars is typically 100 times larger than that from massive main-sequence stars. Their wind velocities are comparable, so the wind ram pressure is 100 times larger for the Wolf-Rayet case at a given distance from the stars. If the radiatively driven flows are comparable in the two cases, the wind bow shock is then 10 times closer to the disk in the Wolf-Rayet case, at a radius of $\sim 10^{14}$ cm, which places it at about the same radius as the photoionization front for nebulae like those in Orion (McCollough et al. 1995). The wind can thus affect the optical appearance of the nebula by making it somewhat more compact.

For a strong, fast flow, like that of a nearby supernova, matter may be stripped from a disk. If the timescale for the flow interaction is longer than the dynamical timescale for the disk, the ram pressure of the flow can come into equilibrium with the gravitational forces maintaining the disk. If the interaction is rapid, the question is whether the momentum in the flow can cause disk material to reach escape velocity. The escape velocity from the outer parts of the disk is $v_{\text{esc}} = (2GM_d/d)^{1/2} = 5.2(M_d/M_{\odot})^{1/2} d_{15}^{1/2}$ km s$^{-1}$, where $G$ is the gravitational constant. The disk dynamical timescale is $t_d = d v_{\text{esc}} = 61(M_d/M_{\odot})^{-1/2} d_{15}^{-3/2}$ yr.

In ram pressure stripping, the disk is disrupted if the ram pressure in the flow, $p_{\text{ram}} v_j^2$, where $p_{\text{ram}}$ is the local density in the flow and $v_j$ is the velocity, exceeds the gravitational force per unit area, $G M_d a/d^2$, which keeps the disk bound to the central pre–main-sequence star. An estimate of the gravitational force per unit area is $p_{\text{grav}} \approx GM_d a/d^2 \approx 2 \times 10^{-3}(M_d/M_{\odot}) M_d d_{15}^{-2}$ dyn cm$^{-2}$.

The supernova case is complicated by the uncertainties in the density distributions of the supernova and the surrounding...
In order to obtain an estimate of the effects, I assume a constant density supernova with ejecta mass $M_{ej}$ and energy $E$ in a constant density medium with H density $n_H$ (assuming a $10^4 : 1$ H-to-He ratio by number). The ram pressure effect is largest if the disk is directly exposed to the freely expanding supernova ejecta, i.e., it becomes placed within the reverse shock wave of the supernova remnant. For a constant density supernova, the maximum radius of the reverse shock is $r_{rs} = 4.4(M_{ej}/10M_\odot)^{1/3}n_H^{-1/3}$ pc (Truelove & McKee 1999). For the values of $r$ considered here, the circumstellar disk is exposed to the expanding ejecta. The maximum ram pressure that can be exerted by the ejecta occurs if the disk is hit by the outer, unaccelerated edge of the ejecta, which moves with a velocity $v_e = (10E/3M_{ej})^{1/2} = 4.1 \times 10^7(M_{ej}/10M_\odot)^{1/2}$ km s$^{-1}$, where $E_{51}$ is in units of $10^{51}$ ergs. The supernova interaction time is $t_{SN} = 200(r/pc)E_{51}^{1/2}(M_{ej}/10M_\odot)^{1/2}$ yr, which is equal to the disk dynamical timescale, $t_d$, for $r \approx 0.25$ pc. For $r \geq 0.25$ pc, the ram pressure stripping arguments are relevant, but for a close supernova, the momentum in the ejecta is the important factor. The peak ram pressure is $P_{ram} = 5E/(2\pi r^3) = 3 \times 10^5 E_{51}(r_{pc})^{-3}$ dyn cm$^{-2}$, which is to be compared to $P_{grav}$ above. A disk at 1 pc from the supernova can survive even this extreme case. At distances smaller than 0.25 pc, momentum transfer causes stripping to occur, beginning at the outer parts of the disk. The criterion for stripping is now that $M_{disk}v_{disk}(4\pi r^2) > \rho v_{esc}^2$. It can be seen that the ram pressure and momentum stripping criteria are roughly the same when the age equals the time the supernova shock wave passed by a radius $r$. 

Stripping is the most likely consequence of a strong flow past a disk, but may be circumstances under which some of the flow is accreted to the disk. The problem with the fast winds from main-sequence or Wolf-Rayet stars or with supernova ejecta is that the wind gas is shock-heated to a high temperature $[10^6 v_e/1000 \text{ km s}^{-1}]^2$ K for hydrogen-rich gas] and the radiative cooling time is longer than the flow time. Unless the gas can mix with the cool disk gas and share heat with it, it is implausible that fast-flow gas can be added to a disk. A slow wind from a red supergiant star can marginally cool in a flow time and gravitational effects can be significant for its accretion. The Bondi-Hoyle accretion rate for a supersonic flow is $M \approx 4\pi \rho v_e^2 \rho_{gas} v_e$, where $\rho_{gas}$ is the local density in the wind and $v_e$ is the wind velocity. Integrating over the time of accretion, the total accreted mass is $2 \times 10^{-4}(M_{ej}/M_\odot)(v_e/10 \text{ km s}^{-1})^2(r_{pc})^{-2}M_\odot$, where $M_\odot$ is the total mass lost during the red supergiant phase.

4. THE EARLY SOLAR SYSTEM

In view of the evidence for the birth of low-mass stars close to massive stars, it is interesting to speculate on the consequences for the proto-solar system if it were born in such an environment. Störrzer & Hollenbach (1999) note that the disks close to $\theta^1$ C Ori ($r \approx 0.3 \text{ pc}$) can have their outer parts photoevaporated by the strong radiation field from the star. They further note that if this applied to the solar system, it could help explain why Uranus and Neptune have considerably less hydrogen than Jupiter and Saturn.

There are further consequences of the solar system being born at $\sim 0.2$ pc from a massive star. When the massive star became a red supergiant, at an age of $(3 - 4) \times 10^7 \text{ yr}$, the solar system would have been enveloped by a slow dense wind. Gravitational accretion of the wind would lead to $\sim 1.4 \times 10^{-7} M_\odot$ of dusty gas being accreted on the solar system, if the massive star lost about $3 M_\odot$ of material during this phase. The late accretion of grains would contribute matter that would not have to pass through the possibly destructive environment of the early solar nebula formation, although the accretion process could lead to grain destruction. The wind material would contain radioactive $^{26}$Al, which is known to have been present at the birth of the solar system (Lee, Papanastassiou, & Wasserburg 1976). The abundance of $^{26}$Al in the wind from the H envelope is $2 \times 10^{-6}$ by mass for a 25 $M_\odot$ star (Meyer, Woosley, & Weaver 1995), so that $3 \times 10^{-13} M_\odot$ of $^{26}$Al might be accreted. This is less than the $3 \times 10^{-9} M_\odot$ of $^{26}$Al that is required if the $^{26}$Al was mixed throughout the proto-solar system including the Sun (Cameron et al. 1995), but it is sufficient to contaminate $1 \times 10^{-4} M_\odot$ of disk gas to the observed level. The initial mass of the protoplanetary disk must be $\gg 10^{-2} M_\odot$, but only part of it may contain $^{26}$Al. Other extinct radioactivities (e.g., Cameron et al. 1995 and references therein) are produced deeper in the massive star and are not ejected in the red supergiant wind unless there is a mechanism to mix them into the outer layers. The inner layers would be ejected past the solar system during the Wolf-Rayet and/or supernova phases, but I have argued above that the high velocity of the gas in these phases makes accretion difficult. If the gas could stick, the picture would resemble the early “flypaper model” of T. Gold (see Clayton 1977, p. 267).

As discussed in § 3, a layer of melted grains may be formed soon after the time of supernova shock wave breakout, depending on the disk position and grain properties. This is of interest for solar system chondrules, which are grains that have been melted (Hewins 1997). In the supernova case, the grains would be rapidly heated by the arrival of radiation at the time of shock breakout, but would cool more slowly because of the continued supernova radiation. There is some evidence that the chondrules were rapidly heated and subsequently cooled on a longer timescale (Hewins 1997). The determination of whether supernova radiation is a suitable heat source will require more detailed calculations.

The supernova gas would have reached the solar nebula tens of years after the explosion. If the disk had already been limited to a size of 10 AU by the earlier action of photoevaporation, the passage of the ejecta would not further disrupt the disk, but it would drive a shock front into the disk. The ratio of $P_{wind}$ discussed above to the thermal pressure in the disk $P_{wind} / P_{th} \approx 10^3 v_{esc}^2 c_s^2$ is typically greater than 10, where $c_s$ is the sound speed in the disk. The pressure due to ejecta approaches $P_{wind}$ and can drive a shock wave. The shock wave propagation depends on the detailed density distribution in the disk. Shock waves in the solar nebula have been a leading explanation for the formation of chondrules (Boss 1996) and provide an alternative to the radiative heating. If cooling of the shocked material is slow, some ablation of the disk gas is possible. The supernova shock wave in the red supergiant wind generates a high-pressure region that envelops the circumstellar disk for tens of years. For a wind mass-loss rate of $3 \times 10^{-6} M_\odot \text{ yr}^{-1}$, $v_e = 10 \text{ km s}^{-1}$, and a shock velocity of $v_{shock} = 4000 \text{ km s}^{-1}$, the pressure is $\rho_{gas} v_{shock}^2 = 6 \times 10^{-6} \text{ dyn cm}^{-2}$, or $10^3$ times the present interstellar pressure. The cosmic-ray energy density is likely to be similarly enhanced because of shock acceleration of particles; relativistic electrons in such shocked layers are observed in the radio supernova phenomenon. Cosmic rays have been suggested as a source of isotopic anomalies in meteorites (e.g., Clayton & Jin 1995), but the energy available in the current situation does not appear to be sufficient for interesting effects.

This speculative scenario of coeval formation of the solar
system and a nearby massive star is an alternative to the hypothesis that the formation of the solar system was triggered by a supernova and that radioactive isotopes were injected at that time (e.g., Cameron et al. 1995; Foster & Boss 1996, 1997). A major difference is that in the present scenario, the early solar system is considerably closer to the supernova and is exposed to a more extreme environment. It is able to survive because of the gravitational binding of a disk to its central star. The unusual environment has a bearing on several perplexing properties of solar system material. The probability that the solar system went through such a phase is small but perhaps nonnegligible. If the Orion Nebula Cluster has a limiting radius of 2 pc, ~0.1 of the solar mass stars are within 0.2 pc of the center (Hillenbrand & Hartmann 1998). The cluster is likely to become sparser as it ages (Hillenbrand & Hartmann 1998), so the probability of a nearby massive star may decline by the time of a supernova. This probability will be better determined by further observations of circumstellar disks in massive star clusters and by studies aimed at finding disks near massive stars in their final evolutionary phases. The proposal made here of a search for transient narrow Hα line emission in the spectra of Type II supernovae is one possibility, although it is only near the more massive supernovae (M ≥ 20 M☉ initial mass) that young disks are likely to be present.

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