Mass Loss and Disk Formation in Rapidly Rotating Hot Stars

Project Summary

One of the longest-standing problems in astronomy regards the origin of the circumstellar disks that cause the characteristic Balmer line emission of classical Be stars. The research proposed here will investigate the dynamics of three potential mechanisms for forming such disks by mass loss from rapidly, but subcritically, rotating hot stars. Our general approach will be to apply and extend the framework of radiation hydrodynamics simulation codes used in our previous studies of the *Wind Compressed Disk* (WCD) paradigm. The initial focus will be to examine the role of radiative driving of discrete mass ejections from localized bright spots on the rotating surface. A second focus will be understanding the possible role of resonances among discrete nonradial pulsation (NRP) modes in triggering such mass ejections. A third focus will be on developing MHD simulations of 'magnetic WCD' models, wherein a dipole field on a rotating star provides a means both to guide outflowing wind material toward an equatorial compressed disk, and to spin it up to a stable Keplerian orbit. These theoretical efforts are inspired by three recent observational breakthroughs in specific Be stars, namely spectroscopic evidence of an NRP mass-ejection connection in μ Centauri, observation of a bright X-ray flare in λ Eridani, and detection of a tilted dipole field in β Cephei. We will also carry out analytic analyses in simplified test cases to augment and test results from the numerical simulations. Finally, our simulations will include generation of synthetic diagnostics in the X-ray, FUV, and UV, and so provide a strong theoretical basis for interpreting existing and planned observations of B stars by various orbiting X-ray and UV observatories.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

Section		Total No. of Pages in Section	Page No.* (Optional)*
Cover Sheet (NSF Form 1207) (Submit Page 2 with original proposal only)			
A	Project Summary (not to exceed 1 page)	1	
B	Table of Contents (NSF Form 1359)	1	
C	Project Description (plus Results from Prior NSF Support) (not to exceed 15 pages) **(Exceed only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**	14	
D	References Cited	2	
E	Biographical Sketches (Not to exceed 2 pages each)	4	
F	Budget (NSF Form 1030, plus up to 3 pages of budget justification)	5	
G	Current and Pending Support (NSF Form 1239)	4	
H	Facilities, Equipment and Other Resources (NSF Form 1363)	1	
I	Special Information/Supplementary Documentation	1	
J	Appendix (List below.) **(Include only if allowed by a specific program announcement/ solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**		

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Project Description

1. Introduction and Background

Hot, luminous, massive stars are significant contributors to the integrated light in galaxies, and their mass loss plays an important role in the dynamical and chemical evolution of both the interstellar gas/dust, and the stars of all masses that form from this. Although many aspects of massive stars are quite well understood, significant stellar rotation poses a challenge for modelling both their evolution and mass loss. An especially good laboratory to study the role of rapid rotation is provided by the classical Be stars, which are among the most rapidly rotating massive stars. Indeed, as discussed extensively at the recent IAU Colloquium 175 on "The Be Phenomenon in Early-Type Stars" (Smith et al. 1999), the physical mechanisms and observed behaviors of Be stars share many commonalities with a wide range of astrophysical objects. (See §4.)

Classical Be stars are main-sequence or subgiant spectral type B stars characterized by Balmer emission (typically Hα) that orginates in a circumstellar disk. Understanding the nature of such stars, and in particular the origin of their circumstellar disks, is one of the longest-standing challenges in astronomy. The observational history of Be stars dates back well over a century (Secchi 1867), and over the many decades there has accumulated an enourmous database to document the many intricacies of the highly variable and complex Be phenomenom (Slettebak and Snow 1987; Balona, Henrichs, and LeContel 1994). Despite this, the level of basic theoretical understanding is still quite limited, with no clear consensus on even the key underlying processes responsible for formation (and, often, the disappearance and subsequent reformation) of the circumstellar disks.

This situation stands in marked contrast to the study of accretion disks in binary systems or protostars (Frank, King, and Raine 1992), for which there is an obvious *outside* source of material that *falls inward* toward the central star. Since classical Be stars are not typically in interacting binaries (Baade 1992), and since (unlike, e.g., Herbig Ae/Be stars) they are clearly inferred (e.g. from Be stars in clusters) to be much older than any reasonable retention time of a protostellar disk, it seems the only plausible source for disk material must be *outward mass loss* from the star itself. Thus in contrast to accretion disks, where the key physical processes involve the *dissipation* of both angular momentum and gravitational potential energy as material falls to the central star, the key challenges in forming Be disks are to identify the physical mechanisms for *addition* of angular momentum and energy needed to lift material from the stellar surface into a stable, rotationally supported, orbiting disk.

Although there is no generally accepted specific model for how this occurs, there is a longstanding concept that it is likely to be related to the quite rapid rotation speeds inferred for Be stars. The general theme of the research projects proposed here is to examine the effect of rapid rotation on stellar mass loss, with particular focus on three distinct processes – radiative driving, non-radial pulsation (NRP), and magnetic fields – that may play key dynamical roles in triggering and/or propelling mass loss that can feed the formation of a circumstellar disk. To provide context for the specific projects proposed in §2, we first briefly review the present state of theoretical understanding and summarize key recent observational results that inspire our proposed research directions.

1.1 Subcritical Rotation & Wind Compressed Disks

Though rapid, the rotation of Be stars is still generally subcritical, with typical inferred surface rotation speeds $V_{rot} \sim 250$ km/s that are only half the minimum speed $V_o = \sqrt{GM_*/R_*} \sim 500$ km/s needed to reach a near-surface circumstellar orbit. This provides the key argument against the simple notion – dating to work by Struve (1958) and continuing in modern "viscous decretion disk" analyses (Saio 1994; Lee and Saio 1991) – that disks might be expelled directly from a critically rotating equatorial surface through viscous diffusion of stellar angular momentum. Instead, the typical minimum velocity boost of $\Delta V = V_o - V_{rot} \sim 250$ km/s to reach orbit represents a substantial requirement of both energy and angular momentum.

For the energy, one attractive possibility is to take advantage of the radiative driving of the stellar wind inherent to such hot-stars (Castor, Abbott, and Klein 1975, hereafter CAK), and use this to feed an equatorial disk. A particularly well-known example is the Wind Compressed Disk (WCD) model (Bjorkman & Cassinelli 1993), wherein conservation of angular momentum tends to focus radially driven material into an equatorial disk-like flow. However, as first clearly illustrated through dynamical simulations by the PI and collaborators (Owocki et. al. 1994), the material from the subcritically rotating star necessarily lacks the angular momentum to form a stable Keplerian orbit, and so must continuously flow *through* the WCD, with inner portions falling back onto the star, and the outer regions flowing away as an equatorial wind. Thus, when compared to the dense, nearly stationary Keplerian disks that are inferred by observations, WCD models generally have a density that is too low (Bjorkman 1994, 1999), a radial flow that is too large (Rivinius et al. 1999), and an azimuthal circulation that is too small (Hanushik 1995). Moreover, *nonradial* components of the radiative driving force (Cranmer and Owocki 1995) tend to further *spin down* the wind outflow (Gayley and Owocki 1999), and can even reverse the equatorward flow that causes the WCD (Owocki et al. 1996).

Clearly then, if radiatively driven outflow is to play a key role in providing the energy to lift stellar material into a circumstellar disk, there must also be a mechanism to provide angular momentum to this material.

The research proposed here will center on two general mechanisms for this, namely spinup by a magnetic moment arm, and discrete mass ejection into near-star orbit.

1.2 Magnetic Spinup of Wind Outflow

One obvious candidate for providing such angular momentum is the moment arm of a stellar magnetic field. Material accelerated outward along a radial magnetic field can be effectively forced to maintain rigid-body rotation law out to an Alfven radius R_A, where the magnetic and flow energy densities are comparable. For a outflow with mass loss rate

rate $\dot{M}$ and flow speed v, the Alfven radius can be estimated as

$$\frac{R_A}{R_*} \approx \frac{B_* R_*}{\sqrt{\dot{M} v}} \qquad (1)$$

where we have assumed the magnetic field declines roughly as the inverse square of the radius from its base value B_* at the surface radius R_*. If this Alfven radius is at or above the corotional orbit radius $R_{cor} = GM_*/V_{rot}^2$, then the outflowing material should have sufficient angular momentum to feed a stable orbiting disk.

In a recent breakthrough, Henrichs et al. (1999) report detection of a ~ 100 Gauss dipole field in the Be star β Cephei, with the dipole axis tilted nearly perpendicular to the rotation axis. For other Be stars, efforts to detect magnetic fields have so far only yielded upper limits, typically on order of 100 Gauss, but simple estimates suggest that even a field below this limit could still significantly influence a Be star's wind. For a typical B-star with radius $R_* \sim 5 \times 10^{11}$ cm, wind mass loss rate $\dot{M} \sim 10^{-9} M_\odot/yr$, and wind outflow speed $v \sim 1000$ km/s, eqn. (1) implies that even modest surface fields with $B_* > 5$ Gauss should extend the co-rotation of the outflow beyond the stellar surface.

So far there have been only limited attempts to model magnetic effects on such a radiatively driven outflow. Friend and MacGregor (1984) extended to line-driven CAK winds the classic Weber and Davis (1967) analysis of how a *monopolar* base magnetic field at the surface of rotating star can affect the rotational properties of the equatorial wind outlow. Their results generally confirmed the notion that a moderate surface field could lead to substantial wind spin-up, but in their focus on analytic critical wind solutions extending to arbitrarily large radii, they did not consider their results in the present context of providing a source of material for a stationary circumstellar disk. More recent 2D numerical MHD simulations by Babel and Montmerle (1997) investigated line-driven outflow in Ap/Bp stars with a very strong magnetic field ($\sim 10^4$ Gauss), and showed how a *dipole* loop configuration channels the radiatively driven wind outflow toward a collision at the top of the loop. Their calculations were focussed on the shock emission as a source of observed X-rays from such stars, but they did also note, though did not pursue, the possible general relevance for disk formation. Ignace, Cassinelli, and Bjorkman (1998) investigated how equatorial wind compression effects could enhance the equatorial plane magnetic fields, but again did not specifically address the question of magnetic spin-up into a disk. As detailed in §2.3, one focus of the proposed research here is to further develop rotating dipole models for Be disk formation, using the observed case of β Cephei as a prototype.

1.3 NRP-Modulated Mass Ejection

In many Be stars, however, there is evidence that disk formation is not through a continuous, smooth wind spun up by a magnetic moment arm, but rather through discrete, perhaps even impulsive, mass ejections emanating from a localized region on the star. A prime example is the B2IV-V star μ Centauri. Like many Be stars, its observational history shows substantial variability on time scales ranging from hours (or even less) to years, indeed with the disk emission characteristics sometime disappearing altogether for months or even years. The recovery of emission over the last decade has been extensively monitored through several intensive spectroscopic observing campaigns (see, e.g., Rivinius et al. 1998a,b, and references therein). The data include time-series of line-profile variations from a variety of lines formed at various levels ranging from the stellar photosphere to the circumstellar disk. Using the pulsational modelling code developed by co-I Townsend (1997), Rivinius (1998) was able to interpret the photospheric line-profile variations in terms of nonradial pulsation (NRP), with a long term phase coherence that allows combination of data over many years to resolve numerous distinct NRP modes, including 4 that are separated by less than a percent from a period of 0.503 day.

Most significant, however, are indications that outbursts in the circumstellar emission lines occur in close coincidence with intervals of phase overlap between two or more NRP modes! Moreover, Rivinius, Baade, and Stefl (1998) have shown that this is stable enough to enable prediction of future outburst epochs, thus making possible the targeted monitoring of such activity in a range of observational wavebands. The specific characteristics of the outbursts – appearance of high-velocity absorptions, rapid (period < 1 day) violet/red (V/R) variation in the emission components, and sudden narrowing with slow recovery of the width of emission peaks – are all suggestive of a model in which material is ejected from a distinct region on the surface, with parts falling back while others enter a low circumstellar orbit, gradually spread in azimuth, and eventually diffuse outward to feed a more permanent outer disk. Observations of other Be stars show moreover that such outbursts are very common, with the best observed cases (e.g., 28 Cygni; Tubbesing et al. 1999) also showing evidence of a similar connection to NRP.

Thus far, such outbursts have received only limited theoretical examination. Kroll (1995) and Kroll and Hanushik (1997) used a smooth-particle-hydrodynamics (SPH) code to simulate the evolution of stellar mass ejections, however under the rather unrealistic assumption that the star rotates at the critical rate. Moreover, the local source ejection on the equatorial surface was, quite arbitrarily, given an initially high outflow speed $v_i = 50 - 200$, thereby effectively circumventing the crucial question of driving mechanism. Nonetheless, a key insight provided by this model is that the ejection as a whole does *not have to be directed* into the sense of the stellar rotation, since even in an isotropic ejection, those elements moving along the rotation undergo a "natural Keplerian selection" as the ones that most easily achieve orbit. In this sense, localized, episodic mass ejections have an inherent advantage over a steady, radially outflowing wind as a mechanism for forming a circumstellar disk. Examining the dynamics of such localized ejections, and their possible connection to NRP and/or magnetic fields, thus provide key themes in the proposed study that we now outline. In particular, in §2.1.1 we describe some preliminary simulations we have recently carried out of a radiatively driven orbital mass ejection (RDOME) scenario for disk formation.

2. Proposed Study

Within the above context, we propose to study Be disk formation through three distinct, but still interrelated, initiatives:

1. Hydrodynamical simulations of mass driven by radiation and/or gas pressure from localized active spots of a rapidly, but subcritically, rotating star.

2. Fundamental study of NRP with rapid rotation, mode overlap, wave leakage, and nonlinear mode conversion.

3. MHD simulations of radiatively driven mass loss from a rotating star with an aligned or tilted dipole field.

The next subsections outline some specifics of these efforts, followed by a brief summary of our planned comparisons with observational diagnostics.

2.1 Hydrodynamical Simulations of Localized Mass Ejection

For the WCD dynamical models decribed above (Owocki et. al 1994, 1996), as well as for other models of *Corotating Interaction Regions* (CIRs; Cranmer and Owocki 1996) or instability-generated clumped structure (Owocki et al. 1988; Owocki and Puls 1999), PI Owocki and collaborators have developed a general radiation hydrodynamics computer code for multidimensional simulation of line-driven stellar winds. The basic hydrodynamic code (called "VH-1", originally developed by J. Blondin) uses the Piecewise Parabolic Method (PPM; Colella and Woodward 1984) with an operator split advection that allows it to be run in one, two, or three dimensions. Our implementation of radiative forces include both multidimensional extensions (Cranmer and Owocki 1995) of the usual CAK form that uses a localized, Sobolev (1960) approximation for line-transfer, and nonlocal, ray integral versions that allow extension beyond this Sobolev approach (Owocki and Puls 1996). With the localized CAK/Sobolev line-force, 2D models can be run overnight on a moderately fast workstation, while 3D models require a few hours on a vector supercomputer like the SDSC Cray T90.

We propose here to apply this code toward 2D and 3D simulations of mass driven by radiation and/or gas pressure from localized active spots of a rapidly, but subcritically, rotating star. The general goal is to investigate the conditions needed to provide the dynamical impulse to eject surface material into a circumstellar orbit. As this effort is inspired largely by the outbursts observed from μ Centauri, this star will provide the central prototype for our parameter choices (e.g., rotation speed, stellar mass, radius, etc.). Extending our earlier models of corotating interaction regions (CIRs; Cranmer and Owocki 1996), we will initially examine 2D models of equatorial plane outflow from a azimuthally localized bright/hot spot on the stellar surface. A key extension will be the inclusion of nonradial components of the driving forces.

As an initial test case, we will examine pure gas dynamic (without radiative driving) models in which the ejection is driven by a localized, intense, flare-like heating at the surface. To achieve the ejection velocities of > 250 km/s needed to reach orbit, we anticipate it will be necessary to heat the ejected gas to temperatures with a sound speed of similar order, $a \approx 100 - 300$ km/s, i.e. $T \approx 10^6 - 10^7$ K. By modelling the density of material needed for a mass ejection rate to feed a disk, we can derive radiative signatures at wavebands from the optical to X-ray, and thereby use existing or future observations to determine whether such a pressure-driven ejection is at all viable. In this context, we note that a "flare" with a sudden (< 1 day) spike in X-ray flux has been detected on the Be star λ Eridani (Smith et al. 1993, 1997). Moreover, limited X-ray observations of μ Centauri show a significantly harder spectrum than for normal B stars (Cohen et al. 1997), and there are plans to monitor this star for X-ray flaring during predicted outburst epochs.

A more feasible model may be to drive such outbursts by radiation pressure via line-scattering. In our previous CIR models, we find that a modest (factor ~ 2) localized increase in brightness leads to increased line-driven mass loss with a slow speed that then interacts with the ambient wind along a characteristic CIR spiral pattern. With inclusion of azimuthal components of the radiative force, it seems possible that material along the edge heading into the rotation direction might be given sufficient impulse from the bright spot behind it to achieve orbital speed. The general goal of our simulations will be to determine the conditions needed for this occur at a sufficient mass loss rate to feed a circumstellar disk.

2.2.1 Preliminary Simulations of Radiatively Driven Orbital Mass Ejection

In the course of preparing this proposal, we have carried a preliminary feasibility study of the potential effectiveness of localized bright spots in ejecting material into circumstellar orbit. Over the past few months P.I. Owocki has reported on these results in invited colloquia and seminars at the University of Delaware and Johns Hopkins University. A summary has also been posted on Owocki's web page at: www.bartol.udel.edu/~owocki/rdome.html. Owocki, Townsend, and Cohen are in the process of preparing an initial Ap.J. paper on these results, and once ready a preprint of this will also be posted at this web address. Here we give a brief summary of the key initial results.

Generally we find that, even with nonradial forces included, isotropically emitting surface spots tend to drive outward-flowing, spiral streams of enhanced stellar wind mass loss, much as in our previous CIR models without nonradial driving (Cranmer and Owocki 1996). For such a "flat-surface" spot, the spot area appears foreshortened when viewed from an oblique angle to one side of the spot. As such, the radiative flux vector tends to be quite nearly radial everywhere, and so the enhanced brightness is simply much more effective in driving material outward than to either side.

However, we have also experimented with several scenarios for mitigating this tendency toward radial driving. One example is a kind of "eruptive prominence" model, for which the radiation is reduced above the spot – as in a dark filament – but strongly enhanced toward the sides.

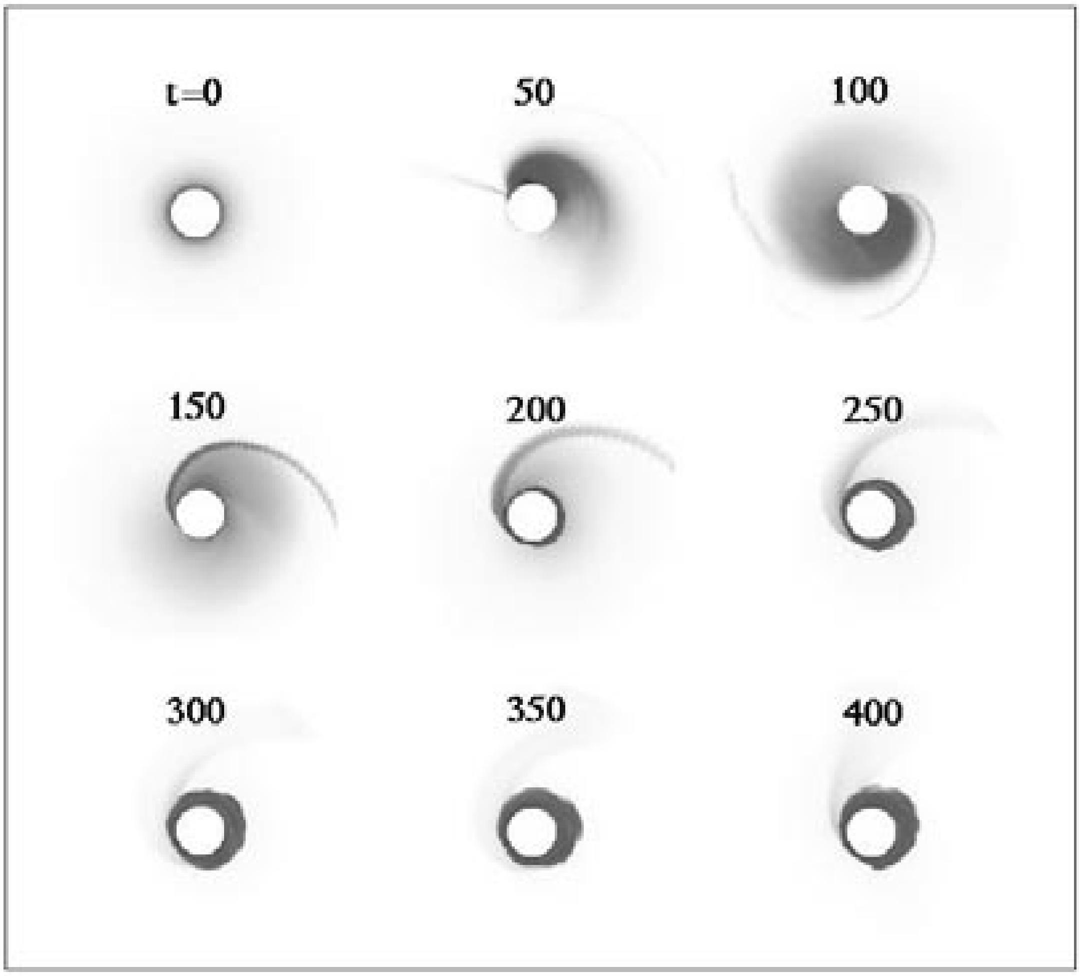

Figure 1: Time evolution of density in a 2D equatorial-plane simulation of “Radiatively Driven Orbital Mass Ejection”. The time interval labels are in ksec (1 day = 86.4 ksec). The model star has a near-surface orbital speed of 500 km/s, an equatorial rotation speed of 350 km/s, and a rotation period of 72 ksec. A localized, highly limb-brightened bright-spot, introduced for an initial interval of 100 ksec, induces a radiatively driven mass ejection. Material ejected ahead of the spot gains angular momentum, and so falls back toward the star into a near-surface orbiting disk once the spot has been shut off.

An idealized simulation of mass ejection from such a prominence/filament model is shown in figure 1. Over a localized equatorial region with a 10^o Gaussian half-width, the brightness is assumed to be reduced to zero in the radial direction ($\mu = 1$), but to be enhanced toward the limb ($\mu = 0$) by a very strong factor (here 100) relative to the ambiant stellar radiation field. The spot was turned on and off suddenly (i.e. as a step function) for an interval of 100 ksec, or about 1.2 day. The stellar parameters chosen were those for a typical B2V star, with an equatorial rotation of 350 km/s, or 70% of the near-surface orbital speed of 500 km/s. The key result is to demonstrate the concept of radiatively driven orbital mass ejection. Material ejected ahead of the spot gains angular momentum, and so once the spot has been shut off, ejected material falls back toward the star into a near-surface orbiting disk.

Of course the conditions assumed in this model are rather extreme and ad hoc, and it remains to be demonstrated whether such orbital ejection can operate under more realistic conditions, tied to a specific disruption mechanism. This will require further extension, for example from current 2D equatorial surface models to 3D cases with bright protusions extending above the surface and out of the equatorial plane. A particular goal will be to examine cases in which such spots follow the pattern of overlapping NRP modes, as developed from a general study of NRP with rapid rotation, which we describe next.

2.2 Study of NRP with Rapid Rotation and Mode Overlap

Co-I/post-doc candidate Townsend did his 1997 Ph.D. thesis on modelling Non-Radial Pulsations. His pulsation code "BRUCE" has since become the standard tool for interpreting line-profile variations in terms of NRP (e.g., Rivinius et al. 1998a). Building upon this and subsequent work on pulsation theory, Townsend will lead our efforts to study the possible role of NRP in triggering disk-feeding mass loss, with emphasis on three parallel and complementary investigations.

The first is an examination of the role of steady-state NRP processes in transporting both energy and angular momentum through the stellar surface and out into wind and/or disk regions. Such a transport process could be achieved via the phenomenon of trans-photospheric wave-leakage; this mechanism has long been known about on a basic theoretical level (e.g., Ando & Osaki 1975), but has undergone surprisingly little in-depth investigation since its inception, especially from the standpoint of its observational consequences. Its interest lies in the fact that it could provide enough angular momentum both to support a circumstellar disk on short time-scales, and to aid in the outward dissipation of a disk over longer time-scales.

The second study regards the interaction between NRP and rotation. It has been shown (eg, Lee & Saio 1990, 1993) that rapid rotation (such that the rotation period is shorter than the co-rotating pulsation period) leads to a confinement of pulsation activity towards the stellar equator, and, furthermore, the introduction of new classes of horizontal velocity fields, which act parallel to the equator. It is possible that these enhanced, equatorially-focussed velocity fields could combine with the underlying bulk velocity due to rotation and carry material beyond its escape velocity, lifting it off the stellar surface primarily around the equator. This mechanism can become especially significant for the case of multiple-mode NRP overlap, as inferred by Rivinius (1997) to trigger mass ejection events. However, current models remain at a basic linear level, and a more sophisticated non-linear investigation of this mechanism is sorely needed.

The final line of investigation looks at the indirect role of NRP in generating magnetic fields, for example, through low-frequency Rossby waves (Airapetian 1999), extended to include quasi-toroidal velocity components of rotationally-modified pulsation modes. For such small-scale fields, reconnection processes could provide the localized heating for the gas or radiation pressure-driven mass ejection described in §2.1. It is also possible analogous pulsational processes could generate large-scale dipole fields, such has been recently inferred for β Cephei (Henrichs et al. 1999). We next discuss our proposed study of how such large-scale fields could spin-up mass outflows into a disk.

2.3 MHD Models of Magnetically Channeled Line-Driven Outflows

As noted in the introduction, another alternative for forming a disk is through a more steady, radiatively driven outflow that is spun up by the moment arm of a magnetic field. We propose here to develop a progressive series of such MHD models, ranging from 1D models with a monopolar fields in the equatorial plane, to 2D models of flows within rotation-aligned dipole fields, and eventually to 3D models of a perpendicularly tilted dipole.

Our initial efforts will be towards reexamining the previous Friend and MacGregor (1984) extension of the Weber and Davis (1967) theory in the context of feeding a circumstellar disk through the line-driven outflow in the equatorial plane of a rotating, magnetized star. A key distinction from their previous wind calculations will be in relaxing the requirement of steady outflow at the outer boundary, allowing instead for connection, mostly likely through an MHD shock transition, from the wind outflow onto a stationary, orbiting disk. This scenario fits naturally with the concept of a detached disk, as is sometimes inferred observationally.

Building on these results for a simple monopolar field, we will then develop MHD models of line-driven outflow in a dipole field. As in our previous hydrodynamical studies, our basic tool in this MHD modeling will be numerical simulations, but now using a version of the standard ZEUS MHD code (Stone 1990; Stone *et al.* 1992) adapted to include our modules for computing the line-driving force. While most of our previous simulations have used the pure hydrodynamical code 'VH-1' described in §2.1, we have implemented a line-driven version of ZEUS, and used this quite extensively to provide independent code test of the VH-1 hydrodynamical results. To confirm the feasibility of the study proposed here, we have already done some experimentation in the full MHD configuration.

Beginning from an initial condition at which the dipole field is imposed on an existing 1D spherical wind outflow, models will be evolved forward in time to an asymptotic MHD flow configuration. The boundary conditions at the stellar surface will be chosen to allow subsonic outflow along field lines fixed by the assumed stellar dipole, taking care to avoid overspecification by imposing (explicitly or implicitly) conditions on outfacing characteristics for the three MHD wave modes. Given the highly ionized nature of hot-star winds and atmospheres, we will generally not include any explicit resistivity, and so, to the extent allowed by the numerical grid resolution, will operate in the ideal MHD limit.

After initial tests of the nonrotating case, we will first investigate the role of rotation in the relatively simple case of an *aligned* dipole field. Since this still retains axial symmetry, it can be modeled in a relatively inexpensive 2D simulation. This case of a rotation-aligned dipole can be viewed as a magnetic version, or alternative, to the simple hydrodynamic WCD paradigm, with magnetic field lines now providing the way to deflect the wind outflow toward the equatorial plane. In this case, however, the fields can also provide a natural lever arm to torque material up to orbital speed, and thus allow for a natural way to feed an orbiting, Keplerian disk. The nature of this 2D dipole field spin up will be compared and contrasted with the 1D radial field results of the Friend and MacGregor (1984) model and with our planned reexamination of this in the context of disk formation.

For the final phase our goal is to develop analogous 3D models of the case with a *tilted* dipole, including the case in which the field dipole axis lies within the equatorial plane, as inferred in the case of β Cephei (Henrichs et al. 1999). For this we will apply recently released public versions of ZEUS-3D. Though such 3D models can be computationally expensive, they are quite feasible on vector supercomputers, and with the most recent release of ZEUS, can even be run in massively parallel configuration.

Through both an existing workstation cluster and a planned Beowolf massively parallel processor run locally within our institute, as well as through our group allocations of time on supercomputers at remote national centers like SDSC, we have access to the computional resources necessary to carry out the simulations described here and in §§2.1-2.2.

2.4 Observational Interface

We further note that an important component of our proposed project will be to derive spectral line signatures from these theoretical simulation models for comparison with observational datasets like that described above for μ Centauri and β Cephei. This effort will draw upon our extensive experience in developing spectral synthesis codes (e.g. Puls, Owocki, and Fullerton 1993). For synthesis of UV wind lines we will apply our existing 3D code based on the standard Sobolev with Exact Integration (SEI; Lamers et al. 1987) method. For optical emission line diagnostics, particularly Hα, we will apply codes developed by collaborators J. Puls and P. Petrenz (Puls, Petrenz, and Owocki 1998). For the flare driven ejection models, the interface with X-ray observations will rely heavily on the extensive experience of D. Cohen. He is leaving his recent Bartol post-doc for an assistant professor position at nearby Swarthmore College, but will continue active collaboration with Owocki. His 1996 Ph. D. thesis at U. of Wisconsin was on X-ray observations of early-type stars, and since 1998 he has been working with Owocki under our NASA LTSA grant to study instability-generated X-ray emission in hot-star winds.

He and collaborators carried out an extensive ROSAT survey of X-ray emission from B stars (Cohen et al. 1997), and he is also involved in several proposals to observe and apply detail spectral diagnostics to B and Be stars, with several additional X-ray satellites, for example *Chandra*, ASCA, and RXTE.

3. Summary of Key Questions and Project Timeline

In summary, we present the following compilation of key questions to be addressed by our study, followed by an outline of the timeline for the specific efforts to be carried out.

- Is episodic mass ejection a dynamically viable model for feeding material into an orbiting Keplerian disk in Be stars?
- For NRP modes on a rapidly rotating star, what are the possible effects of wave leakage, mode overlap, and nonlinear steepening in triggering such mass ejections?
- What role can radiative forces play in outward driving, dispersal, or spin-up/spin-down of ejected material? How might this be connected with NRPs?
- In rotating stars with dipole fields, what is the nature of the equatorial deflection and spin up of wind material, and how does this depend on rotation rate, relative strength of field vs. wind, and tilt between the field and rotational axes? Can this lead to a stable, orbiting disk?

With the proviso that research is inherently an exploration that generally can't be planned too far in advance, we offer the following timeline for our specific efforts to address these questions over each of the next three years:

Year 1. Building on his ongoing studies of radiatively driven stellar winds, Owocki will carry out 2D dynamical models of discrete mass loss from localized active spots. Building upon his ongoing studies on NRPs, Townsend will investigate key issues like wave leaking, that are central to providing lower boundary conditions for the wind models. Concurrently, Owocki, with Townsend's apprenticeship, will examine 1D models of wind-fed disks with magnetic spin up, and begin tests of 2D Zeus model of a nonrotating wind in a dipole field.

Year 2. Owocki will extend the mass ejection models to 3D, applying input from Townsend's NRP studies, which will focus particularly on the role of mode overlap. Concurrently, we will extend our MHD studies to the aligned dipole rotation case.

Year 3. Townsend will focus on nonlinear effects that could trigger mass loss outbursts, with further application to Owocki's 3D hydro models. Concurrently, we will extend our MHD studies to the case of a perpendicularly tilted diplole field.

Thus, in general, PI Owocki will concentrate on tasks related to dynamical modelling of mass loss, while Co-I/post-doc Townsend will focus on investigation of NRPs and their role in triggering and possibly driving mass ejections. In addition to these direct efforts by the named investigators, we expect significant contributions from our collaborator David Cohen, and from Owocki's Ph.D. student Asif Ud-Doula. Cohen will provide the key interface for application of our models toward understanding X-ray observations. Ud-Doula's ongoing doctoral thesis research is focussed on applying the Zeus MHD codes to study magnetic modulation of hot-star winds; he will thus also provide assistance to Owocki's application of Zeus toward magnetic models of disk formation.

We note that the general phenomenon of Be stars is highly complex, with different stars showing quite different behaviors, ranging from examples of relatively steady, permanent emission to cases with extensive variability, including extended periods of complete disappearance of emission, as noted above for μ Centauri. It is thus possible that quite different types of processes may be needed to understand the different cases. As such, the study proposed is not aimed toward developing a single, definitive model, but rather toward exploring the basic dynamical issues underlying mass loss with rapid rotation, and how the various contexts of this could provide mechanisms for disk formation.

4. Broad Space-Astrophysics Relevance of Proposed Study

As discussed extensively at the recent IAU Colloquium 175 on "The Be Phenomenon in Early-Type Stars" (Smith et al. 1999), the general Be phenomenon can have relevance to a broad range of stellar objects. The observed behaviors share many commonalities with, for example: Luminous Blue Variables (LBV); B-supergiants with forbidden emission (B[e] stars); protoplanetary nebula and Herbig stars (PPN & H-Ae/Be); central stars of planetary nebulae (CSPN); cataclysmic variables (CV); and even quasars and active galactic nuclei (QSO/AGN).

Moreover, the research program described above emphasizes how the understanding of Be stars requires consideration of a wide range of physical processes and phenomena – radiatively driven mass loss, non-radial pulsation, rapid stellar rotation, magnetic fields. Individually or in various combinations, these fundamental processes also play key roles in many other astrophysical systems on scales from planets to galaxies, for example solar and stellar magnetic activity; helioseismology and asteroseismology; radiatively driven winds in hot-stars, magnetic T Tauri stars, and QSO/AGNs.

For Be stars, the main issue regards the respective roles of these processes in the formation of the circumstellar disk. Disks are also a common general phenomenon in astrophysical systems over a wide range of scales, including planetary ring systems; protostellar nebulae; stellar binaries; and active galactic nuclei and quasars. However, the above are all examples of *accretion* disks. By turning the usual accretion disk processes "inside-out", the Be problem provides an interesting counterexample that forces a broader understanding of the dynamics of disk formation and dissipation. Indeed, the study of Be stars offers some key advantages relative to these other disk systems, for example: relatively simple geometry compared to binary accretion; direct observability without obscuration, as by a nascent protostellar dust cloud; and human time scales which allow direct monitoring of disk formation and dissipation.

In summary, Be stars provide an important laboratory for studying the role of several key astrophysical processes in the formation and demise of an orbiting circumstellar disk. The results of the study proposed here would have relevance in variety of other contexts, e.g. nonradial pulsation or magnetic activity in stars, and evolution of disks in binary and protostellar systems.

5. Summary of Project Strengths

Finally, we offer the following summary of key reasons for support of the proposed project.

- The puzzle of the Be phenomenon has a long history dating back over a century, and continues today to attract a broad international research community, as evidenced by numerous IAU sponsored conferences, including most recently the July 1999 IAUC 175 in Alicante, Spain.

- However, much of the research focus to date has been weighted toward observation. On the key issue of disk formation, much theoretical work has been at the "cartoon" level, with few attempts so far to apply modern computational power and tools toward fundamental models that incorporate key dynamical processes.

- Recent observational breakthroughs – e.g. discovery of an NRP/mass ejection connection in μ Centauri; X-ray flaring in λ Eridani; and a tilted dipole field in β Cephei – provide clear directions for detailed theoretical investigations involving specific physical mechanisms.

- The investigators are uniquely well qualified to carry out such theoretical efforts. The PI has an extensive background in dynamical simulation of hot-star mass loss, including pivotal studies on the applicability of WCDs to Be stars. He has given invited talks at numerous international meetings on Be and other massive stars, including the recent IAUC 175, and has attracted funding for several projects that augment and complement the effort proposed here. The co-I/post-doc candidate is recognized as a rising star in the Be/massive star communities. His Ph. D. thesis on "Non-Radial Pulsation in Early-Type Stars" received the Royal Astronomical Society prize for the best British astronomy thesis in 1997. This thesis led to development of several useful publicly distributed codes that have already become the standard tools for the NRP interpretaton of observed line profile variability.

- The phenomena and processes central to this study – disks, radiatively driven mass loss, NRP, rapid rotation, magnetic activity – are, in various combinations, also of central importance to a wide range of astrophysical systems on scales from planets to galaxies. In particular, the key theme here of disk formation via stellar mass *loss* provides an instructive counterexample to the usual case of mass *accretion* disks.

6. Relationship to PI's Previous and Current Research Projects

PI Owocki's extensive experience in the background areas of the research proposed here includes involvement in several related past, current, and proposed projects. The general emphasis on the time-dependent dynamics of wind structure laid the basis for key aspects of the current proposal (viz., §2.1 and 2.3), though the focus here on disk formation is quite distinct.

Current efforts include Owocki's NASA/LTSA project to study X-ray generation by radiatively driven wind instabilities, and a collaborative NASA/ATP project with former Bartol post-doc K. Gayley (now Assistant Professor at U. Iowa) to examine radiative braking of colliding stellar winds in massive-star binary systems. Again the specific emphasis in each of these projects is clearly distinct from that proposed here, but they do provide a substantial infrastructure of expertise and codes for modelling complex radiation hydrodynamical processes that form the basis of the above proposed studies of Be disk formation.

For the future, a proposed collaborative project with colleagues J. Hillier and D. Turnshek at the University of Pittsburgh centers on radiatively driven outflows from luminous accretion disks as models of broad absorption line clouds in QSO/AGNs. If funded, Owocki's formal time committment for this is limited to just one month; but we nonetheless expect the focus on disks in a different context than Be stars will provide another useful complement to the present proposed work.

Of the above current projects, only the NASA/LTSA will remain for a significant period into the time frame of the project here. The NASA/ATP project with Gayley has formally expired, but is in a no-cost extension till June 20001. Likewise, a separate NASA/HMGI project – which applies Owocki's earlier Ph.D. thesis to interpretation of the ionization state of the solar wind – will end fall 2000. Largely to enable Owocki to make the major committment needed for the research proposed here, we do not plan to seek renewal of these other current projects.

Finally, we note that we have recently submitted a very similar proposal to that outlined here to the NASA Astrophysics Theory Program. Should this NASA/ATP project be partly funded, we will reduce accordingly the funding requests of the current proposal to NSF. If this NASA/ATP project is fully funded, we will withdraw the current proposal.

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