Discussion Session 4a: Structure and Dynamics of Circumstellar Disks

S. P. Owocki (Moderator)

1. Introduction and Topic Outline

S. Owocki: Before summarizing the issues listed in the program for this discussion session on disks, I first have this slide of van Gogh’s “Starry Night”, which I like to show when I give a public lecture, since the swirls really evoke to me the swirling nature of “Disks in Space”. I was very impressed at this meeting with how the very reserved and polite, but very competent, Japanese scientists were 15 years ahead of us in developing the “decretion disk” scenario for Be disks. I think this slide suggests that van Gogh was a hundred years ahead.

H. Henrichs: “v an gHoff” [Dutch pronunciation of van Gogh]

S. Owocki: Oh excuse me, “v an Gggghhhoff”! [laughter]

Anyway, this discussion is on the “Structure and Dynamics of Circumstellar Disks”, and the key issue is: how do we launch material into a disk, like a Be star disk? Now, we haven’t yet had anyone show this picture here [see left panel of fig. 1], taken from the very nice Ph.D. thesis by Peter Kroll in the mid-90’s. Because it was in German, it didn’t get as much attention as it might have otherwise, though there was a conference paper with Peter Hanuschik [(Kroll & Hanuschik 1997)]. Kroll carried out Smoothed Particle Hydrodynamics (SPH) simulations in which he put a localized outburst on the equatorial surface of a critically rotating star. He found that ejected material settled into a Keplerian disk. In my eyes this work had a lot of influence on subsequent ideas for disk formation.

Now the questions that are listed in the program are:

• What causes Be star outbursts?

• What is the interaction of rotation, wind, pulsations, and magnetic fields in formation of disks?

• What are the pros and cons of current models of disks?

• What are the implications of observations for disk models?

As those are all general questions, I’ve compiled a somewhat more specific list:

• Can we all finally agree that Be disks are Keplerian? Or are there still some dissenters? I think there are, but perhaps, unfortunately, many are not here.

• Is μ Cen a “Rosetta Stone”? For me the work by Rivinius et al. (2001) on this star has had tremendous influence. But is it instead perhaps a “Red Herring”? (A Red Herring in colloquial English means something bright
Figure 1. Left: SPH simulations of disk formation by mass ejection from localized disruptions on the equatorial surface of a critically rotating star, as taken from the Ph.D. thesis by P. Kroll. See also Kroll & Hanuschik (1997). Right: Illustration of how shear in a Keplerian disk (at bottom) implies a strong line-of-sight velocity gradient, $dv_z/dz$, for limb or off-center photons, even in the absence of the radial velocity gradient found in a stellar wind expansion (at top).

and attractive that you chase after, but actually is not what you’re looking for.) Or is it perhaps a “Rosetta Herring”? [laughter]

- **What is the role of magnetic fields, both for large, steady fields vs. small, transient fields?** Through the work Asif ud-Doula and I have done, I think we have made clear our view that large-scale, steady fields are very hard to use to make the kind of Keplerian disk we infer for Be-stars. But I think Thomas Rivinius made a very important comment earlier that this does not exclude the possibility that there could be small-scale, transient fields that play a key role in the ejection mechanism.

- **What is the role of pulsation in mass ejection into a disk?** Is it a trigger or a driver, in pushing things over the top, into orbit. The latter, as we have seen, (probably) requires near-critical rotation.

- **Finally, what observations are needed to constrain these questions?** For example, first for the rotation speed, $V_{rot}$, but also, if we want to find how close to critical these stars may be, we also need to tie down the critical (or orbital speed) $V_{crit}$. Neither one of these is trivial. Then we also want observations to constrain the properties of these disks, if they
are Keplerian, or if they contain outflows. And finally, we want to identify
diagnostics for disk ejection mechanisms.

So now I’d like to open the floor to discussion of these questions, and then there
are a few more items I’ll add later on. So does anybody want to pick up more
generally on the first or second list? David?

2. Nature and Variability of Disks

D. McDavid: I’ll risk this because I think there may be someone here who might
remember what I’m thinking about. It seems to me that some time in the mid
to late 80’s there were a couple of papers by somebody like Dachs or Hanuschik,
where they had emission line profiles from Be disks for which they concluded
that the best explanation included a combination of rotation and radial outflow.
Does anybody remember seeing that?

S. Owocki: Well, whatever historically may have occurred, certainly Hanuschik’s
latest work seems to come down very clearly in the camp of very small radial
outflow. Does everybody agree with that?

Th. Rivinius: At least in the region that we probe with optical lines, I think the
radial outflow is really constrained to be a few km/s.

J. Bjorkman: Following up slightly from Rivi’s comment, going in a slightly
different direction. I think, what convinced me that the disks have to Keplerian
is in fact this observation that the radial outflow velocities in the disk have to
be very, very subsonic, or at least very, very small. And the problem is that
you have forces pulling on the gas in the disk. And if you don’t want the gas to
move radially, you have to balance the r-component of the force somehow. And
you have to do it over a range of radii in the disk, etc., etc. That means that
you’re in a situation where there’s an extreme fine-tuning problem. You have to
fine-tune something that exactly balances gravity. Radiation forces are typically
hard to fine tune, because as you start moving the flow, the radiation force, the
line-driving force, goes up. So it’s hard to hold the radiation force exactly in
balance. One force, however, that is easy to fine tune is the centrifugal force,
just simply because of angular momentum conservation. This is how orbits
work. So the beauty of Keplerian disks is that this fine-tuning through angular
momentum conservation allows you to exactly balance the radial gravity force
with centrifugal force. This strongly, theoretically, to me implies that the disks
have to be Keplerian.

O. Chesneau: I have a question. I have seen many observations that come from
the star, typically NRPs, or emission lines that are interpreted to come from
the disk. But Be stars have a wind, and I would like to know if we can rule out
any wind signature, in the optical or infrared, and keep only the wind signature
in the UV? Or do we have some wind signature that would “corrupt” some
interpretation in the spectroscopy, or even in the interferometry, so that you
can think that you have an outflow or a wind from the disk. It’s not clear in my
mind what is the influence, and the interface between the wind and disk. What
effects could we expect from that?
Th. Rivinius: As far as the wind in the UV, if I remember correctly, this is very strongly inclination dependent. In shell stars, you have no wind signature. There are only shell lines, also in the UV, like in Pleione. And the wind signature of these stars, if you go to inclinations where you see the stellar surface, directly, along a line of sight without intersection going through the disk, and if you can go even further, pole-on, the stronger wind signature that you have in Be stars compared to B-stars dies out, at even higher, er...lower, inclinations.

K. Bjorkman: What about in the infrared?

Th. Rivinius: I think in the infrared it is so, if I remember it right, there is some implication for outflow, but this flows at hundreds of stellar radii, rather than ten for the optical.

R. Townsend: I think something that often gets overlooked is the puzzle of where the clock for Be stars comes from. For those early-type stars that form disks in episodes rather than as a continuous process, what sets the formation and dissipation time of, you know, a few years? In the study of the Earth’s atmosphere, there is a study of something called the quasi-biennial oscillation, which is a sort of speeding up and slowing down of certain flows in the atmosphere. And this happens on, what I think is a 26-month cycle. And how that cycle comes about is sort of non-trivial, but it is due to an interaction of a number of different phenomena, all coming together, all with a separate characteristic periods, and they all mix together to give this 26-month period. And I’m just wondering if in Be stars there are a number of phenomena that act together to give a sort of recurrence time of a few years, in a quite non-trivial and non-obvious way.

S. Owocki: Yes, I think one of the lessons, for me, is that Be stars are individuals. Each one has its own peculiarities. And from my point of view that’s very interesting, but what we want to do, in this case, is to try to see the grand patterns, and also trends, you know, between the early types and late types. Jiri?

J. Kubat: Concerning what you said, that Be stars are individuals, I think that this is a selection effect, because we are interested in those stars that are variable, because you can write an easy paper on the variation. You can’t write anything about non-variable stars. And if you look at the set of Be stars which are unobserved, it is a terrible amount of stars that are not studied at all. So I am a little afraid that we are studying only the most prominent and most variable stars.

S. Owocki: Yes, “The squeaky wheel gets the oil”, as we say in English... Karen is shaking her head [yes]. So that can important. There’s a selection effect. We tend to pay attention to the most variable objects. Jon? Or is there somebody else who had their hand up before Jon? Huib?

H. Henrichs: Coming back to Rich’s remark, magnetic fields have the tendency to be variable. Except in these neutron stars or white dwarfs, there is no object that has a steady magnetic field. They all have turnover timescales, and are generated by things like dynamos. Many of them have short timescales, the sun for instance. There’s an example.

R. Townsend: That’s a very local magnetic field. I think it’s important to draw a distinction between the sun’s magnetic field – which is a very local, variable
field – and the sort of large-scale, global fields we seem to be detecting in early-type stars. These early-type stars may also have local, variable fields, but the large-scale fields seem to be quite steady over, you know, significant timescales. I mean, you just...

H. Henrichs: No, I’m talking about the small-scale fields. This example of $\tau$ Sco is a wonderful example, I think, that this is small-scale field. That’s the thing I was thinking of.

S. Owocki: It remains to be seen how variable $\tau$ Sco’s field is. It could be complex, but quite steady. We’ll have to see over the years if it changes. Certainly, $\sigma$ Ori E’s field, as far as we can tell, hasn’t changed in 30 years.

H. Henrichs: Yes, but that’s the wrong example. To find a short period...

3. Disk Ejection Mechanisms

J. Bjorkman: Moving on to the question now of how the heck do we get the material into the disk. Rivi’s results on $\mu$ Cen I find rather intriguing. Now this of course has the caveat that $\mu$ Cen might be a psychologically deviant Be star, however the thing that struck me is that at the beginning of the outburst he is showing a small absorption component blue-shifted at 200 km/s. Now, at face value, that indicates you might be ejecting material at 200 km/s, in the radial direction, off the surface of the star. This of course is very surprising for us if we think this has anything to do with pulsations. But if it is true that you can eject material at 200 km/s, then we don’t need to have stars rotating at critical to get material going off the star into the disk. What we really need is a way to transport the angular momentum into that material to put it into orbit – hence magnetic fields.

S. Owocki: Yes, and I think in this regard, for me, the major lesson of the Kroll simulations – if we can go back to that slide quickly [left panel of fig. 1] – is that you can eject material, more or less hemi-spherically, from the surface of a rotating star, and that material that is heading in the direction of the rotation will tend to go into orbit, and everything else will fall back down. So one of the key lessons of these simulations is that you don’t need a “guiding mechanism”, as in a finely guided rocket. You just need to have enough energy to get into orbit, and that material that is heading in the right direction will go into orbit.

J. Telting: Can g-modes, which have horizontal motion, can they have high enough velocity in the right direction? Are g-modes consistent with the finding of having stuff going 200 km/s in the radial direction?

Th. Rivinius: The linear answer is “no”.

J. Telting: The “linear” answer?

R. Townsend: I think, this is something John brought up with me yesterday, that we like to think that g-modes can’t produce any velocity field that is much greater than the sound speed. [...] Of course, our understanding of nonlinear effects in stellar nonradial pulsations is very poor, because it is such a difficult subject. But at least in the case radial pulsations, John quite rightly reminds me of the case of BW Vul, which has velocities of up to 150 km/s. Now the
situation may be rather different with nonradial pulsations, but certainly this is something that we really need to start looking into, you know, just how fast a nonradial pulsation can accelerate material. Now I think there are very fundamental reasons that it can’t be hugely greater than the sound speed. But then from what Jon says, obviously there’s material being flung at 200 km/s, and it seems to be tied in with the pulsation beating, so what’s going on there?

S. Owocki: Yes, I think one of the key distinctions for me is the question of p-modes, which are compressive modes, and they can’t really get much greater than the sound speed, because the faster stuff will just run into the slower stuff, steepen into a shock, and then dissipate. But g-modes are circulations, and it might seem there’s no reason why you just can’t keep accelerating it nonlinearly to make it go faster and faster. It’s just that our understanding of g-modes is that buoyancy plays a role in driving this circulation, and since that’s rooted in the gas pressure, it’s hard to understand how it can get much faster than the sound speed.

R. Townsend: Also, with g-modes the horizontal restoring force is still pressure. I mean buoyancy is only the vertical restoring force.

S. Owocki: That’s exactly my point. So, for g-modes it’s not quite as fundamental an argument. And then as far as BW Vul, of course, that’s a radial pulsator and so the mode has its root much deeper into the star, and therefore the sound speed is much higher there, and that’s why you can have a large amplitude. Cepheid variables, for example, have very large amplitude pulsations because they’re deeply rooted inside a hot star.

R. Townsend: I mean, the same can be said for g-modes, because they are being driven deep down at the iron opacity bump, exactly where BW Vul is being driven, so who knows?

R. Schnerr: Well, there’s one thing I haven’t understood since the beginning of the conference, but I thought everybody would know. But then I asked people at the conference, and it seems I’m not the only one who cannot completely oversee this topic with critical rotation. Because people talk about stars that rotate at 95% of critical rotation, but then I ask George Meynet, why would a star stop spinning up at 95% of critical? If the core contracts and the star spins up, why would it stop at 95% critical, or even critical, because what’s critical for the star is not critical for the core? So it might be that the core just spins up a lot, like 105% of critical if you extrapolate that through the whole star. And then it transports out this angular momentum, and you just naturally create a disk. And so formation of disks would be quite easy, from that point of view. The question is more how you get rid of this disk when it stops. Of course this would only work for stars that are actually critically rotating, which runs into trouble whether they actually are or not.

S. Owocki: Yes, I think this was really Struve’s [1931] original idea, that Be stars are critically rotating and they just have to get rid of angular momentum, and do this by shedding a disk. I think the reason we talk of them being slightly subcritical is that we say that there is some mechanism before they get to critical that starts to spill over. They don’t have to get to critical. And the fact is Be star disks are not very dense, unlike B[e] star disks, which are really dense, and
form dust. Be star disks are relatively low density. They come and go. They mainly show up in Balmer lines. They are optically thin in the continuum. They only have 1% polarization. If they were very dense, and the stars were really supercritical, they would show much more polarization, wouldn’t you say... no, Karen?

K. Bjorkman: You have to be careful about that. [...] The one percent polarization is because you see the star, and the star is largely unpolarized, so it dilutes the polarization. But the fact that you get the low polarization is just a result of the fact that you see to the star. In pre-main-sequence stars, where the star is hidden, there you can get 50, 60, 70 percent polarization, no problem. But not in Be stars.

S. Owocki: But, in general, Be star disks are not that large in mass. The mass in the disk is only about $10^{-10} M_\odot$. If they were really super-critical, they would eject a large fraction of the envelope. Jiri?

J. Kubat: For B[e] stars, I can hardly imagine a dense medium can produce forbidden lines.

J. Bjorkman: Apparently they’re not dense everywhere. [...] More seriously, the density drops actually fairly steeply with radius in one of these decretion-disk models, i.e. as $r^{-3.5}$ if it’s isothermal. That’s a tremendous drop-off in density. So you’re probably just picking up the forbidden emission lines from intermediate radii. [...] It [also] falls exponentially with the disk scale height as you move above the surface.

S. Owocki: And at the meeting in [Vlieland] Holland this summer [(Kraus & Miroshnichenko 2006)], one of the points that Michaela Kraus made was that when you have dense disks, it’s cool, and then by recombination you actually get rid of a lot of the free electrons, which are what de-excite the forbidden line emission. And so this makes it easier to get forbidden lines in moderately high densities.

4. Disk Destruction

S. Owocki: Okay, does anyone else want to chime in on any of these points here? No? So before we finish up, I just want to go to one more subject, which is the destruction of the disk. Because Atsuo [Okazaki] brought it up in his talk that if you have a disk by the viscous decretion disk model, and you keep this disk fed properly, it reaches a steady state. Unfortunately, if you overfeed it tend to grow, and some of us have that problem in our own lives! [laughter] But if you feed it steadily, it just reaches a steady-state, whereas if you shut it off, it tends to have material diffuse back on the star, as well as outward. Diffusion is a two-way street; it goes in both directions. And so when you have a density maximum at the base, it will diffuse outward. And when you have the ejection shut off, it will diffuse inward, as well as outward. So that’s one possibility, that the viscous disks decays because material diffuses inward and outward.

But another possibility, which we talked about before, is that there is ablation. This can be either due to entrainment with the stellar wind, or due to forces acting on the disk. One of things that is important to realize is that a
Keplerian disk, even though it has no radial velocity, has a tremendous amount of shear. Now we normally think that line-forces are important because of the velocity gradient of a stellar wind. The arrows in this figure [right panel of figure 1] represent the increasing velocity of the stellar wind, and the curve plots the velocity gradient, here for a simple beta=1 law. And it’s this velocity gradient, which leads to a deshadowing of the lines for photons moving in the radial direction, that’s what makes line-driving efficient for a wind.

But if you have a Keplerian disk, it’s important to realize that photons that are also coming from the limb. So even though there is no wind, no expansion, there is a tremendous amount of shear in the disk, because it’s Keplerian, and because of that (i.e., the resulting velocity gradient seen by these limb and non-radial photons), line forces can actually be quite important. Now, they’re not as important as in a wind because the density is so high. But in terms of perturbing the disk, it gives a possible mechanism for precession of the one-arm modes. And also, from the surface of the disk, this can give a very effective method for ablating the disk away. And indeed, as we talked about yesterday, we often see evidence that the disk is a source of the wind, not the other way around. You see that if a star with Be shell lines also has wind lines, it would be evidence for disk ablation.

So one key question we have is: which one of these possible mechanisms for destroying the disk is the operative one? Does anyone want to offer an opinion about that?

J. Bjorkman: If you ask yourself the question, does the wind come from the disk, then I’m thinking about other situations where there are disk winds, for example, potentially CVs have disk winds. Maybe, Stan [Owocki], you could answer this question, but can we think about this as scaling up a little bit. I mean, the primary difference is that we have a lower gravity star in our Be-star disk, and so the effective gravity that you’re fighting to push material away from the disk is correspondingly lower. That should mean that you have correspondingly higher mass loss rate from the disk. If I remember correctly, for CV disks you’re making of about $10^{-13} M_\odot$/year.

S. Owocki: Yes, of course, it depends a lot on the luminosities. And models of CV disk winds don’t quite work because the star is not bright enough. You’re using the star’s light to ablate the disk, and in CV disks, the central star is not that bright, so it’s actually a bit hard to get a line-driven wind. I think it’s actually much more promising for Be stars. And the whole point is, this should be going on all the time. It’s just that during times when the disk is not being replenished, then it disappears. But during times when it’s being constantly replenished, this disk wind is just a little bit of “peeling off” of what is otherwise viscous diffusion. Olivier?

O. Chesneau: Just to mention the work of Janet Drew [and collaborators, (Oudmaijer et al. 1998)] in the case of B[e] stars. I think in my memory it is the only disk with wind which has been proposed for hot stars, in the case of HD87643.

S. Owocki: Yes, well it’s another issue that we haven’t really had a chance to talk about. But there’s a debate going on in the B[e] community as to whether the disk in that case is a Keplerian disk, or an outflowing disk. And it’s actually similar to the debate that’s gone on in Be stars. It’s just at an earlier phase.
One of the differences is that for B[e] stars, there are only a few of them. And I think we’re very awash in data in Be stars. There are lots of Be stars, which is a blessing, and also from my point of view, sometimes a curse. But the possibilities for testing models is much greater. Whereas for B[e] stars, there are just a handful of objects known in the galaxy, and couple more in the Magellanic Clouds. Jon, do you want to make a comment?

J. Bjorkman: If it what’s I remembering, this is a different kind of B[e] star. It’s a pre-main-sequence kind of thing. And I think in that model, the wind was being driven by a self-luminous disk. In other words, there was enough accretion luminosity being liberated in the disk that the disk is strongly emitting. It is in fact the dominant luminosity source, which makes it a lot easier to push a wind off the disk.

S. Owocki: That happens in quasars, for example, as well. Ok, let’s see, Jiri, do you have a final point to make here?

J. Kubat: I would suggest another mechanism for this destruction, namely bina-

rity. I remember five years ago, John Porter made a simple calculation ([Porter 1998, 1999]). He took a star with a disk, and put a tiny companion star into the
disk. This star really cleaned the disk, in just a few orbits.

S. Owocki: Yes, certainly Atsuo’s [Okazaki] simulations actually show that very

nicely. I was speaking in this context about destruction of single-star disks. Atsuo, comment?

A. Okazaki: In John’s simulations, he assumed a big disk from the beginning. But the disk can’t grow big in binary systems. The disk is truncated. So you can’t destroy the disk as a whole by a companion. If the torque is cut off in a binary system, then the outer radius is fixed, and the density is almost constant. Only the inner part accretes, and the density distribution becomes flatter and flatter.

5. Concluding Remarks

S. Owocki: Any final comments? If not I’d like just to close here by mentioning how I end my popular talks on Be stars. I think one of the things that has plagued our field is that we’ve been looked on as being this isolated community. But I think we are looking at a class of objects that provide really a very interesting laboratory. And to emphasize my point in a dramatic way, that these stars could really be rotating very close to critical, I like to make the analogy of what would it be like if we lived on a planet that was close to critical.

Now the Earth has a surface orbital speed of about 18,000 miles/hour – sorry, I usually give this talk to an American audience; it translates to about 30,000 km/hour. The Earth’s rotation is about 1000 mile/hour, a little above the speed of sound, as it turns out. But what if a day on the Earth were, instead of 24 hours, about an hour and a half. Then the Earth would be a critical rotator! And so instead of “Stop the world, I want to get off”, which is a common phrase in colloquial English, it should be “Spin the world up, I want to get off! Because it would be very easy to get off the Earth in that case. The Earth would be a flattened, oblate surface. There would be a disk around
it. Indeed the Earth-moon system was formed by the collision of a body the size of Mars with the proto-Earth. And perhaps, 4.5 billion years ago, that is what the Earth did look like. And in this case, instead of having to rely on an expensive, chunky, unreliable source to get into orbit, all we would have to do is all take a trip to the equator... and jump! So you wouldn’t need the space shuttle anymore, and I think that would be a blessing. Thank you for your attention and participation. [applause]

References


Ryuko Hirata (upper left), Thomas Rivinius (upper right), and Philippe Stee contributing to the discussions.