STRONG EMISSION LINE PROFILES FROM T TAU Ri STARS

Gibor Basri
Astronomy Department, Univ. of California, Berkeley

1. INTRODUCTION

The classical T Tauri stars were originally discovered by virtue of their strong Hα emission, which is the most outstanding characteristic distinguishing them from normal late-type stars in the optical part of the spectrum. There have been great advances in our understanding of these objects since their identification by Joy (1945) as an interesting class of stars. We now understand them to be pre-main sequence low mass stars, at most a few million years old, still surrounded by accretion disks of gas and dust. We know they have strong magnetic activity, are rotating slowly compared to breakup and rapidly compared to old main sequence stars, and have strong associated mass loss. There are excellent recent reviews of T Tauri stars by Bertout (1989) and Appenzeller and Mundt (1989).

Yet the original identifying characteristic – strong line emission – remains today the least understood part of the T Tauri phenomenon. Almost no statement concerning the physical formation of the Hα line (not to mention the many other strong permitted lines) can be said to have a consensus behind it. This is due in part to the remarkable variety of line profiles observed from different stars, in part to the sometimes striking variations seen in profiles from a given star at different times, in part to the complicated radiative transfer effects that might play a role, and mostly due to the lack of an accepted physical paradigm to explain the line formation region.

In this review, I first discuss the observations. These have been greatly aided during the last decade by the advent of CCD detectors coupled to full-frame echelle spectrographs. This allows much higher S/N high resolution spectra to be obtained on these rather faint (for coudé observation) stars, with a number of
interesting diagnostic lines obtained at the same time (which eliminates confusion caused by rapid line variability). These improved observations are only now beginning to appear in the literature in quantity. A review of profile observations with some interpretation has been given by Bertout (1984), and other papers of interest are Basri (1988), Basri and Finkenzeller (1987), Appenzeller, Jankovics, and Jetter (1986), Mundt (1984), Hartmann (1982), and Mundt and Giampapa (1982). I then discuss some possibilities for the line formation – what mechanisms could give rise to the types of profiles observed? This is done from both the radiative transfer perspective, and with a couple of possible models for the physical characteristics of the line formation region. Rather than a review of accepted results, this discussion is more in the nature of posing a few possible hypotheses which the work of the 1990’s will support, reject, or modify.

2. OBSERVATIONS

2.1 The Balmer Lines

The Balmer lines are seen in emission in classical T Tauri stars (CTTS) almost by definition. There is indeed a class of low-mass pre-main sequence stars for which this is not the case, but these are called “weak-line” T Tauri stars (WTTS) and are distinct from the classical stars in their lack of both strong Balmer emission and near infrared excesses. The dividing line between the two is usually set at an Hα equivalent width of around 10Å, since that was the detectability limit of the original objective grating surveys. This has no physical significance, and Hα strengths can be found in a continuous distribution on both sides of this limit. Even more confusing is the fact that the equivalent width depends as much on the underlying continuum as on the flux in the line, so a given equivalent width implies different emission measures for different spectral types (it is easier to see a given intrinsic amount of emission against a fainter cooler photosphere). I will discuss the stars whose Hα lines are stronger and broader than those from the most active older stars; namely those whose line emission would be hard to explain with a classical stellar chromosphere (even one covering the entire star).

The most common Hα profile seen in CTTS is a broad (≈500 km s⁻¹ base width) emission feature with a peak somewhat sharper than a Gaussian of the same FWHM and an absorption feature in the blue wing centered near −100 km s⁻¹ which does not go below the continuum. The DF Tau Hα line in Fig. 1 is an example of this. The emission wings are often nearly symmetric about the stellar rest velocity outside the absorption feature. Somewhat more rarely, the absorption feature occurs near zero velocity, is in the red, or there are multiple absorption features. The more symmetric profiles with absorption features tend to occur in stars with weaker emission. In a few cases, the profile peak appears broad,
sometimes even flat. Other examples of the Hα lines are shown in Fig. 1, each with a different character. The strength of the emission increases to the right.

In stars with high peaks the absorption is often broader and occasionally the absorption feature will go below the continuum. This absorption is usually at higher velocities, but a few cases of narrow central absorption below the continuum are also known. In very strong profiles extended faint wings can be seen to reach out to 1000 km s\(^{-1}\) or more; these are probably due to electron scattering of the bright emission line. There are almost no cases in which redshifted absorption is seen below the continuum in Hα. It is common for both the absorption and emission features to show mild changes from night to night, and sometimes the changes are very striking. There is also a class of profiles which show no absorption feature, which tend to be symmetric or at least peaked at zero velocity.

The higher Balmer lines sometimes resemble Hα. When they are different, they tend to be more symmetric and the emission is weaker relative to both the absorption and continuum. The absorption features more often extend below the continuum, and this can sometimes be seen redward of line center (if so, the star is called a YY Ori star). The Hδ lines for 5 stars are shown in Fig. 1; for each star all the profiles shown are from the same epoch. The equivalent width of the absorption tends to diminish up the series, as does the velocity of the feature. Flattopped profiles become more common. Not surprisingly, it is in the cooler stars that the high Balmer lines are most prominent, since they occur in the part of the spectrum where the photospheric flux is rapidly diminishing in these stars. Especially in the hotter stars, there may be very little apparent emission in the higher lines. There are a few cases, however, where even the high series lines are purely emission features with no absorption apparent.

2.2 Other Strong Lines

The next most important optical lines in the spectra of CTTS are those from singly ionized calcium. Both the resonance H and K lines and the infrared triplet are usually seen strongly in emission. Of course, the triplet lines are much easier to observe since they occur near the flux peak of the stars and the peak sensitivity of CCDs, while the resonance lines lose on both counts. In the WTTS and mild CTTS, these lines resemble their counterparts on active main sequence stars. They are relatively narrow (<100 km s\(^{-1}\) base width), symmetric, and centered on zero stellar velocity (see DN Tau in Fig. 1). Indeed, they probably arise from similar regions, namely strong magnetic activity on or near the stellar surface. As the Balmer lines become stronger, one begins to see the presence of a broader component in first the resonance lines and then the (optically thinner) triplet lines. The narrow component begins to be overwhelmed by the broad component (see BP Tau in Fig. 1).
Figure 1. Nearly simultaneous observations of 4 strong emission lines in 5 classical T Tauri stars. The vertical scales are different, but the horizontal scales are all in km s\(^{-1}\), ranging from -500 to +500 in the stellar rest frame. The dates of observation are: DN Tau – 1986 12 Nov., BP Tau – 1986 21 Dec., DF Tau – 1986 23 Oct., DR Tau – 1987 12 Oct., RW Aur – 1986 21 Dec. All observations were made with the Hamilton echelle spectrometer at the Lick Observatory, by the author.

Figure 2. Time series of the H\(\alpha\) line in 4 classical T Tauri stars. The epochs of observation are: DR Tau – 1989 31 Oct. 5:30UT, 11:45UT; 1 Nov. 5:30UT, 12:40UT; 2 Nov. 6:00UT; DF Tau – 1988 10,11,12,13,14 Feb.; RW Aur – 1988 12,13,14,16,17 Feb.; AA Tau – 1989 2,3,4,5,6 Dec.
In the strongest emission stars, only the broad component is seen and the lines begin to resemble the Balmer lines (see RW Aur in Fig. 1). Absorption features (in addition to the common very cool narrow components formed either quite far from the star or in the ISM) appear in the resonance lines when the lines are broad enough, and appear in the triplet lines in the most extreme cases (see RW Aur). When seen in the triplet, they tend to have relative strengths proportional to the oscillator strength. The typical broad triplet lines are symmetric, without absorption features, and more peaked than Gaussian (see DR Tau). While they tend to have nearly equal strengths in this case, there are some cases in which the optically thinnest line actually has the highest intensity. The H line profile is complicated by the presence just to the red of it of He, and sometimes also by a flourescent iron absorption feature.

The HeI 5876Å line is also seen fairly commonly in emission. It tends to be a narrow symmetric zero-velocity feature in the stars with weaker Balmer lines, develops the narrow/broad two-component nature in stronger stars, and can have a purely broad component in the strongest emission stars. An absorption feature is rarely seen. This line is typically not seen in the hotter stars. The HeII 4686Å line is almost never seen. The NaD lines are always seen, dominated by the strong broad stellar absorption. Multiple narrow blueshifted components tend to be present in stars with strong blueshifted Hα absorptions (and sometimes redshifted NaD is also seen). Somewhat broad central emission features will often be present in such stars as well. This can lead to very complex composite profiles.

Other emission lines are seen in the more extreme stars, including FeI, sometimes FeII, and a number of other species. Flourescence is known to play a role in the presence of some of these. Their profiles tend to be somewhat broad, symmetric, triangular, and typically without absorption features. In the more extreme stars, they tend to appear similar to the high Balmer lines. I do not discuss the very interesting forbidden line emission which is seen in many of the stronger emission stars, since it likely arises in a region well away from the star itself.

2.3 Line Profile Variability

The fact that the emission lines are rather variable in CTTS has been known for a long time. They can change their equivalent widths and shapes in a few hours. The main sorts of changes are either in total strength, strength and position of absorption feature, or symmetry of emission peaks. The red wing is probably the least variable part of the profile. The timescale of variability gives an indication of the size of the line formation region, while the nature of the changes are powerful diagnostics of the unsteady processes going on. Presumably the non-variable parts of the profile tell us about the parts of the line formation region.
that are relatively stable (and therefore more fruitful for detailed modeling). Unfortunately, there are few really systematic studies of profile variability published, although there are ongoing projects to rectify this.

I present four illustrative cases in Figure 2. The relative intensity scale is the same throughout. In the top row are profiles from DR Tau obtained over 3 successive nights. They are separated by intervals of 7, 16, 7, and 16 hours respectively. At first the line looks much like the canonical T Tauri Hα profile with red peak higher than blue, and blueshifted absorption. Later that night the blue peak has gone, and the red peak is a little higher. There is still a shoulder on the blue wing, but it is not obvious that the blue peak has been masked by increasing blue absorption rather than having merely diminished (which also makes the interpretation of the original profile more ambiguous). The trend is continued on the next night, where now the blue wing rises smoothly if asymmetrically to the red peak. Later that night a clear blue absorption feature is seen again, at higher velocity and now below the continuum. It seems confined to high velocities, although there is still a clear shoulder at the lower velocity. The next night the profile is quite similar and a double nature for the high velocity component more evident, but the red peak is somewhat fainter.

The next row shows 5 consecutive nights of DF Tau Hα profiles. The profile is characterized throughout by a peak that rises from the red to zero velocity, and then is cut off steeply on the blue side. The first night there is just a shoulder, but the next night a clear blue absorption develops. The third night the entire profile is somewhat brighter, then the fourth night it becomes quite faint, while preserving its shape (except that the peak is flattened). A huge increase in brightness occurs on the last night. This is followed on successive nights (not shown) by a fluctuating decrease, and the absorption feature is sometimes absent again.

The third row shows consecutive nights of RW Aur profiles, with a night missing between the third and fourth profiles. There are fluctuations in the intensities of both peaks and in the breadth and symmetry of the absorption feature (though the position of the minimum is remarkably constant). Note that the peaks change dominance over the missing night, but that the higher peak is actually on the side of the absorption feature with the shallower slope (contrary to what we might expect if the absorption feature were the agent of the asymmetry). Longer strings of data leave one with the impression that each feature of the profile changes independently of the others. Changes in the total breadth also occur, and the center of gravity of the whole profile can shift.

The bottom row show 5 consecutive nights of AA Tau profiles. This is a much weaker star, but it shows relatively large changes. On the first night there is a slightly blueshift absorption feature, steep blue wing and shallower red wing.
next night is fainter and the red peak is essentially gone. On the third night the absorption now appears to the red (it is often at zero or redward velocities in this star). After that the profile redward of line center changes little, but the blue peak jumps up on the fourth night and subsides on the fifth.

It is clear from these examples (and there are many others with different behaviors) that modeling line profiles is a difficult business for CTTS. A nice detailed model constructed for the first DR Tau profile will yield something rather different than one for the fifth profile. It would seem that long strings of data are needed to characterize the average appearance of the profiles, and to categorize the nature and extent of the possible changes. It is also clear that the processes involved in these changes have a lot of power at their disposal, occur within a few stellar radii, and do not depend on a particular detailed scenario being set up and maintained. If the profiles arise in the turbulent interaction between a somewhat unsteady accretion disk and ever-changing powerful magnetic field lines on the stellar surface (which rotate past each other at several hundred km s\(^{-1}\)) then the observed changes do not seem unreasonable. This is particularly true if the wind component arises directly as a result of this violent interaction, rather than depending only on gross properties of the star or the accretion disk. I note that while more study is needed, it does not seem that the same sorts of phenomena are observed in the WTTS, where an accretion disk is not thought to be present.

3. FORMATION OF STRONG PERMITTED EMISSION LINES

3.1 Chromospheric Line Formation

It was noticed early in the study of CTTS that many of the emission lines observed are also seen in the solar chromospheric eclipse spectrum. In addition to the Balmer and CaII lines, many of the FeI lines seen in the stronger emission stars fall into this category. This led to suggestions that magnetic activity might be responsible for the CTTS lines directly. The reason that lines appear in emission in a classical stellar chromosphere is that the temperature structure (or more properly the line source function) actually begins to rise towards the outside of the star above the photosphere due to non-radiative heating of this lower density plamsa. On the Sun, however, this rise occurs above the region of formation of most spectral lines. This means that the full-disk optical spectrum of the Sun contains virtually no emission lines (the CaII H and K lines being a very mild exception). The H\(\alpha\) line on the Sun, despite being optically thick in the chromosphere, is not in emission due to the non-LTE nature of the line source function.

In order that magnetic activity account for T Tauri emission lines, the chromospheres on those stars would have to occur at much greater line optical depths.
It is true that such conditions are more closely met if one looks only at solar active regions, and that very active main sequence stars show much more line emission (or at least filling in of line absorption) than does the Sun as a star. Thus it is at least worth considering whether magnetic activity can produce the emission lines. Since even the most active main sequence stars do not approach the emission levels of the CTTS, one would have to posit much stronger magnetic activity. This is not a priori unreasonable, since magnetic activity is known to decay with age, and the TTS are very young. Detailed model analyses (Cram 1979; Calvet, Basri, Kuhi 1984) showed that the total line fluxes of the CaII and MgII lines could be met with very deep chromospheres, and such activity would also explain the observed filling in of absorption lines and the ultraviolet continuum excess. Indeed, it has been shown that the ratio spectrum of a TTS with a matching spectral standard has many of the characteristics of a solar eclipse spectrum (Pinkenburg and Basri 1987), even when most TTS lines are only filled in rather than actually in emission. If emission lines are formed on the star or in magnetic loops attached to the surface, one would expect them to be relatively narrow and symmetric. The narrow central lines observed in TTS are therefore compatible with this explanation.

The difficulty with such ad hoc models is that they have no physical justification. It seems impossible to come up with a mechanism that would cause a major fraction of the star's bolometric luminosity to appear as non-radiative heating in the upper atmosphere, as required by the continuum veiling. Another major problem is the breadth of the strong emission lines. To interpret them as "opacity broadened" (requiring the source function in the wing to also be raised) would mean an atmosphere that would show none of the weaker absorption lines that are typically visible. To interpret them as velocity broadened requires that hypersonic turbulence be maintained in the relatively dense conditions in the upper stellar atmosphere. This is as difficult as the non-radiative heating problem mentioned above. Rotational broadening can be eliminated both on the basis of the line shapes and on the known slow rotations derived from the absorption lines and rotational modulation. Thus it seems necessary to posit an energy source other than the star to explain the strong broad emission lines. Accretion disks provide a natural such source.

3.2 Spherical Line Formation

I now begin the task of briefly describing how various line profiles can be produced from various physical scenarios. In its most general form, this problem is very difficult and its solutions are non-unique. When one allows arbitrary geometries for the line emitting region, arbitrary velocity laws within them, and arbitrary spatial variation of the line source function it is possible to produce almost
any line profile in a variety of different ways. While stars will not avoid such complications just to make the analysis tractable, it is also not useful at this time to be too detailed. Thus we consider highly idealized cases, and hope that we can explain enough features in the spectrum with a simple model that it actually tells us something about the physical configuration at the star.

The simplest case to start with is to confine the emission to the star itself. If we suppose there is a single line profile intrinsic to the stellar surface, there is an analytic solution to the function that must be convolved with it to account for stellar rotation. This is basically parabolic, and if the intrinsic emission is narrow compared to it, a parabolic flux profile will result. The next simplest case is a spherical optically thin line formation region that is extended compared to the star. Here the profile depends on the visible volume that emits at a given frequency. Bertout and Magnan (1987) have summarized these cases in a simple analysis. The appearance of the profile now depends on the width of the intrinsic local emission line to the rotational and/or expansion velocities that could be present. If there is expansion (or accretion), it also depends on the gradient of the expansion velocity. With a constant expansion velocity, one will get a rectangular flattopped profile, whose sides will reflect the behavior of the local line profile. If the extension of the region is not much bigger than the star, part of the redshifted side of the profile will be occulted. Putting in an expansion law will tend to enhance the parts of the profile that are formed at the geometrically most extensive velocities. As these tend to be lower projected velocities on the limbs of the shell, the profile assumes a rounded peaked appearance. All this assumes that the line source function is constant; obviously with gradients one can emphasize the part of the atmosphere where the source function is brightest.

In the optically thick case the profile just depends on the visible area which emits at a given frequency. Of course, the area which is visible can depend on the macroscopic velocity field, since a velocity gradient can shift the profile to uncover deeper layers. For high velocity gradients, the Sobolev approximation provides a method of calculating the profile (and even the source function in simple cases). The extent of uncovering also depends on the intrinsic width of the local line profile. For high gradients, the profile can be parabolic, flattopped, or bowl-shaped (inverted parabola) depending on whether the logarithmic velocity gradient is greater than, equal to, or less than unity. For low gradients, one can get a saw-toothed profile with central minimum under certain conditions (a narrow shell) or at least a central reversal; if the local velocity width becomes too large the profile becomes flattopped again. The above cases assume constant source function.

In a more physically realistic case, the line source function may reach a peak at some radius, and then decrease at larger radii while the velocity accelerates up to some terminal value. This means that the line wings will be formed at lower
velocity while the core is shifted and darker compared to the inner wings. The winds produced by cool stars are not expected to have a very high velocity gradient compared to the local line width. This will produce a broad profile with asymmetric peaks (brighter on the red side) separated by a blue-shifted reversal (that typically does not go below the continuum). Such profiles are seen in resonance lines from red giants, though they are usually much less broad than lines in TTS. The line width is largely due to wing opacity. For the breadth seen in TTS, a highly turbulent component seems likely. The reversal in this case is due to the optically thickest material having a low source function (rather than due to a primarily geometrical effect), and the blueshift is due to the assumption of an accelerating expansion. Since this generally fits the description of a T Tauri Hα line, such wind models have remained of great interest.

The most fully developed model to date is the Alfvén wind model (DeCampli 1981; Hartmann, Edwards, Avrett 1982; Lago 1984; Hartmann et al. 1990). These assume spherical symmetry, and that the wind is driven by deposition of momentum by Alfvén waves in the stellar magnetic field. The wave dissipation and stellar magnetic field strength are the main parameters of the model, and are adjusted to fit observations. These models are characterized by high turbulent velocities near the star, and the temperature typically rises to $10^6$K or less, with terminal velocities of 100–200 km s$^{-1}$. These models tend to produce modified P Cygni profiles, and it is difficult to get the blue peak high enough or the absorption to stay well above the continuum. Their virtue is that they are physically self-consistent calculations (within the assumptions). They can reproduce the basic line widths, fluxes, and Balmer decrements observed.

Their flaws are that the crucial wave dissipation is essentially *ad hoc*, and that it is unlikely that the star by itself is responsible for T Tauri winds since they only occur when there is evidence of an accretion disk and are not seen in the WTTS. On the positive side, there is increasing evidence that the stellar magnetic fields are in the required range, and that their interaction with the disk can produce some kind of magnetic wind that will do the trick. There are some new ideas about how Alfvén waves might drive winds (An et al. 1990) which may put the wave driving mechanism on a firmer foundation, but these remain to be applied to the CTTS case. Centrifugally driven winds (eg. Shu et al. 1989) must also seriously be considered (several papers with such models by various theorists are currently in the preprint stage).

3.3 Axisymmetric Line Formation

There are several good reasons for supposing that the actual line formation region in TTS is not just spherical. Certainly, the presence of a disk tends to defeat this assumption, unless the disk is optically thin in the line formation region.
Even if it is, however, the wind may be forced to flow up and away from the disk regardless of whether one can see through it. Finally, young stars have been observed to produce both bipolar CO outflows and sometimes bipolar optical jets, and Herbig-Haro objects usually occur in a bipolar configuration. It is natural, therefore, to consider biconical, ring, and disk geometries for the line formation region.

In a ring, a bowl-shaped profile with sharp outer cusps will result if rotation is the dominant velocity present. If strong turbulence is present it will tend to fill in the bowl and broaden the outer sides of the profile. Of course, if the turbulent velocities far exceed the rotation, one gets essentially just the profile of the turbulence. If the ring is not too big compared to the star, the profile will remain symmetric since both approaching and receding material is in front of the star. Tilting the ring will tend to reveal more low velocity material first, making the bowl shallower. A disk can be viewed as merely a series of rings, each with a different velocity. This will tend to render the cusps less sharp, but still leave a bowl-shaped or centrally reversed profile since that results from the relative lack of material moving at right angles to the observer. In the usual case (Keplerian rotation) the slower moving parts of the disk will also subtend more area, tending to fill in the bowl somewhat. The fact that very broad central reversals are almost never seen in TTS argues fairly strongly that the lines are not simply formed in a disk around the star, since the rotation velocities near the star are high enough to produce the above effects. An exception to this seems to be found in the FU Ori stars, at least for absorption lines (Hartmann and Kenyon 1987).

Conical geometries can be viewed as sections of spheres, so some of the statements about spherical geometries apply, particularly at the wider opening angles. A good discussion of conical profiles when occultation by the star is not a factor appears in Edwards et al. (1987). The main extra factor is now the viewing angle to the axis of the cones, and of course parts of the spherical profile will be absent. One can produce self-reversed profiles in this case purely through geometrical effects, which sometimes look like observed profiles. Further effects result from considering hollow vs. filled cones.

Very recently, Calvet and Hartmann (1990) have calculated Alfvén wind models with conical geometries. They find that this improves the match with observations significantly compared to the spherical cases, reducing the incidence of classical P Cygni profiles and allowing the profiles that are commonly observed to be produced more naturally. One disturbing point is that the profiles sometimes radically alter their shape within a day – not necessarily in ways that have easy geometrical explanations.
3.4 Turbulent Line Formation

Despite the popularity of the wind interpretation for TTS emission lines, De-Campli (1981) pointed out that the symmetry of the outer wings of the lines was probably better explained by turbulent broadening, and indeed mass loss is only really required to explain the blueshifted absorption features. Of course, one can included high turbulence into a wind model, as is required for the Alfvén wind models discussed below. Closer examination of the typical TTS profile reveals differences from those produced by most wind models: the profile often retains a symmetry even near the peak once the absorption feature is accounted for, the profiles tend to have sharper peaks than the models, the behavior of the line wings is rather independent of the position of the absorption, and sometimes even the peak asymmetry can switch without much change in the position of the absorption feature.

An alternate interpretation of the line profiles (which I favor) is that the emission is produced in a fairly small region near the star with hypersonic turbulence as the primary line broadening mechanism, and the absorption feature is produced further out in a somewhat independent region. The variability of the lines suggest this, since the emission and absorption seem to behave fairly independently of each other. The symmetry of the line wings has a natural explanation if turbulent, and the amount of turbulence has a natural explanation in the accretion disk model. It is very easy to model production of line profiles if turbulence dominates, the profile will just be the turbulent profile or the sum of turbulent profiles if different turbulent velocities are allowed. The sharper than Gaussian nature of the profiles can be explained if a range of turbulence is assumed; the lower turbulence concentrates its power near the line peak and the higher turbulence contributes more to the wings of the line. This of course assumes that all the turbulence is visible, either for geometrical reasons or because the problem is effectively optically thin.

A nice set of profiles demonstrating several of the effects I have discussed can be found in Hartmann, Edwards, and Avrett (1982; their Fig. 3). I have also computed a set of very simple computed composite profiles to illustrate. In Figure 3 I show in the upper left panel the effect of including a range of turbulence. By itself, it tends to produce profiles sharper than Gaussian. If one now allows the turbulent region to be shifted by expansion (even constant velocity expansion as in the lower left panel has a range of projected velocities) then one gets profiles flatter than Gaussian, and even flattened if the turbulence is low enough compared to the shift. In the right hand panels I show the constant shift, variable turbulence case with weightings of the cosine or sine of the angle to the observer in the individual profile intensities. No occultation by the star has been included (it will tend to reduce the red side of the line). The former has similarities to the
Figure 3. Composite profiles made by adding Gaussians with different widths, sometimes shifted and weighted by different amounts. Upper left – Unshifted profiles of equal weight with FWHMs of from 30 km s\(^{-1}\) to a variable upper amount: 90, 120, 150, 180, 210 km s\(^{-1}\). These represent profiles arising from a region with a range of turbulent velocities visible, and are more peaked than single Gaussians. Lower left – similar to upper left, but with an additional shift of up to ±210 km s\(^{-1}\) applied to each family of Gaussians. The upper limits to the turbulent velocities are 30, 90, 120, 150, and 180 km s\(^{-1}\). Such a shift could arise from expansion of the region, and the profiles are flatter than Gaussian. Righthand panels – same as lower left except a weighting function is now applied to the projected shift. Upper right – weighting by the cosine of the angle to the observer, with upper turbulent limits of 30, 90, 150, 210, 280 km s\(^{-1}\). Lower right – same as upper right but with a sine weighting. These mimic either a wind with appropriate velocity gradient, or rotating ring respectively (see text).
case of a rotating star, or the spherical optically thin case with the right gradient law. The latter case is like a rotating ring or disk, or the spherical case with the other extreme of velocity gradient law. Of course the more the turbulence is dominant, the closer the profile comes to a Gaussian (or sum of Gaussians).

With the addition of absorption components (after the fact) to one of these family of profiles, one can do a fairly good job of reproducing most of the observations. This supposes that these components come from a cooler, less turbulent part of the flow that occurs after its primary acceleration in the hot turbulent region near star and disk. That is not to say, of course, that therefore the observations are actually explained in this way. Detailed models which explain a variety of diagnostics are needed before we can really say much. The differences between this and the Alfvén wind models described above become increasingly blurred if the main wind driving occurs in a turbulent region within a couple of stellar radii, caused by the interaction of disk and stellar magnetic field. There is a convergence on ideas about the stellar magnetic field being a crucial ingredient, about a dense turbulent region at the base of the wind, and about the necessity of an accretion disk (Cabrit et al. 1990). Some essential features of the Alfvén wind are preserved in this scenario (with its ability to explain gross properties of the lines), while the details of the line formation and its variability may become easier to fit into this model than in the Alfvén wind model as originally conceived. It would then also be fair to say that the lines and wind are formed primarily in the interface region between star and disk, although again the original boundary layer ideas were too simplistic.

It seems inescapable that the volume of new high quality observations now just emerging on the T Tauri stars will greatly sharpen and constrain our ideas on the formation of their strong emission lines. I would be very surprised if by the end of this decade, a much more highly developed and accepted explanation for these enigmatic profiles had not been found. This in turn, will be a valuable addition to our understanding of star formation, very young stars, mass loss from cool stars, and the interaction between accretion disks and magnetic fields. It therefore is a very fruitful area of current research.
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