Accretion Disks

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Flat Stars

1. Background Perspective

One of the major developments of mid-twentieth-century stellar astrophysics was the understanding that there is often a third "object" in a binary star system, especially in a system undergoing mass transfer. Matter from one star swirls around the other forming a configuration known as an *accretion disk.* Such disks were first recognized in the study of white dwarfs in binary systems. With the advent of X-ray astronomy, it became especially clear that accretion disks play a prominent role in binary systems containing neutron stars and black holes. In many circumstances, the accretion disk is the primary source of visible light; in others, the disk is also the primary source of X-ray radiation; and in yet others, the disk channels matter into streams of outgoing material and energy. One dramatic fact is that, without accretion disks, we would not yet have discovered any stellar-mass black holes.

One star in a binary system must undergo mass transfer to feed the disk the matter needed for the disk to exist at all. The disk forms around the star receiving the transferred mass. An accretion disk thus also depends on a more ordinary star (considering black holes to be "ordinary" in this context!) for the gravity to hold the disk together. Given this support from the two stars in the binary system – one to provide matter, one to provide gravity – the accretion disk then effectively has a life of its own. The accretion disk has a structure and evolution that depends only incidentally on the properties of the star at its center or the one providing it mass. The disk is almost like a separate star, a flat star. The disk generates its own heat and light and can have eruptions that have nothing directly to do with either of the stars.

2. How a Disk Forms

In common situations, the matter that feeds the disk flows from the companion star through the inner Lagrangian point that connects the two Roche lobes in the binary system. The structure of the inner Lagrangian point makes it act like a nozzle. The matter thus leaves the mass-losing star in a rather thin stream in the orbital plane of the two stars. In reality, the matter may spray in a messier fashion, but most of the matter remains in the orbital plane. If the two stars were stationary, this matter would flow from one star directly along the line connecting the centers of the two stars and strike the mass-gaining star. In a binary star system, however, the stars are constantly moving in orbit, so the mass-gaining star is a moving target. The matter may leave the mass-losing star headed for the other star, but because the other star moves along in its orbit, the transferred matter cannot fall directly onto the mass-gaining star.

If the mass-gaining star is small in radius, and white dwarfs, neutron stars, and black holes all qualify in this regard, then when the mass flow first starts, the stream of matter will miss the mass-gaining star entirely, passing behind the star as the star moves along in orbit. The gravitational domain of the mass-gaining star captures the matter, however, so the stream circles around and collides with the incoming stream. As this process continues, the flow of selfinteracting matter will form first a ring and then a disk. From that point on, the transferred matter will collide with the outer portions of the disk and become incorporated into the disk.

The process by which the self-colliding stream of matter becomes an accretion disk involves the angular momentum of the matter in a crucial way. When the stream of matter first circles around the mass-gaining star, it has a certain angular momentum with respect to the star it orbits. Conservation of angular momentum forces the matter to move in a circular path of a certain size. The size of this path depends on the motion of the two stars. If the matter just stayed in this path, it would form a ring, somewhat like the rings around Saturn. To form a filled-in accretion disk that extends all the way down to the surface of the star, the material must settle to ever smaller orbits. Matter in a smaller orbit will have a higher velocity, but the net effect is still to have a smaller angular momentum. Only if the orbiting matter loses some of its angular momentum can the matter move inward and settle onto the central star. The angular momentum must be conserved in the whole binary system, but the matter in the disk must transfer some of its angular momentum elsewhere. Without this loss of angular momentum by the disk matter, the matter would stay in a ring. With a loss of angular momentum, the matter can settle inward, forming a full-fledged accretion disk.

One of the remarkable things about accretion disks is that they are structured in just such a way to provide for this transfer of angular momentum elsewhere, as illustrated in Figure 4.1. Kepler's third law tells us that because the matter in the disk that is closer to the central star must have a smaller orbit where the gravity is higher, matter in a smaller orbit must move faster. Thus each piece of material in the disk finds the material just beyond moving a little slower, and the material just within its orbit moving a little faster. The result is an inevitable rubbing of all the orbiting streams of material on all the adjacent streams. Each stream is slowed down by the slower, outer, adjacent stream and is thus forced to spiral inward. The result, ironically, is for the matter to end up moving faster because the material picks up energy from the gravity of the central star. This process is fundamentally the same one that caused a star to heat up as it lost energy, as we discussed in Chapter 1. The effect of conservation of energy in the presence of gravity is to gain speed (or temperature) when some energy is taken away from the gravitating matter. The result of the rubbing and slipping inward is that the matter gradually settles onto the surface of the star. This process of gradual addition is known by the general term *accretion*, and hence the resulting flat structures are known as accretion disks. The angular momentum that is lost from the disk is gained by the orbiting stars or perhaps blown from the system by winds. The total angular momentum is, in any case, conserved.

3. Let There Be Light – and X-Rays

The other important aspect of the inescapable friction that causes the matter to spiral in and accrete on the star is that friction heats the matter in the process. The heat escapes as radiation that astronomers can study. Because the orbital velocities are lower in the outer portions of the disk, the amount of slipping, friction, and heat are relatively low. The outer portions of the disk are typically about as hot as the surface of the Sun and emit much of their energy in the optical portion of the spectrum. In the middle of the disk, the velocities are higher, the friction and heat are greater, and the energy characteristically emerges in the ultraviolet portion of the spectrum. This is the end of the story if the mass-gaining star is a white dwarf, because the matter spiraling inward in the accretion disk collides with the white dwarf before the matter gains substantially more energy. For neutron stars and black holes, however, conditions can get even more extreme.

The velocity of the spiraling matter can get near the speed of light. The frictional heating is immense. The matter gets so hot that the radiation emerges as X-rays, as shown in Figure 4.2. This is one reason that the search for neutron stars and black holes in binary stars requires X-ray instrumentation. Those instruments work best on satellites above the absorbing atmosphere of the Earth, so the astronomy of neutron stars and black holes has been primarily one of the space age. We will tell this story in Chapters 8 and 10.

4. A Source of Friction

The study of these flat stars called accretion disks has been a major undertaking in astronomy over the last three decades. The understanding of accretion disks is still in a somewhat crude state. The situation is analogous to the early days of stellar evolution when there was an understanding of the balance between pressure and gravity, but the power source of stars was not known. The problem was that nuclear physics had not been invented. For accretion disks, the physics that determines the heating of the disk is known in principle, but its application is very complex in practice. The net effect is much the same. The drawback for accretion disk theory is that we do not know the nature of the friction, and so the mechanism to generate heat in the disk remains an important unknown.

We know that the normal microscopic rubbing of molecules in a gas is vastly insufficient to provide the friction and heat in observed accretion disks. Rather, the friction must come from large-scale roiling in the disk. Work of the last few years has provided evidence that magnetic fields must play a role in this process to generate the turbulent roiling motions and to couple one eddy in the complicated flow to another to make the interaction and the friction effective.

One compelling theory is that any magnetic field in the disk becomes naturally and unavoidably stretched in the orbiting matter in the disk. A simple analog of the process is to imagine a satellite connected to the space shuttle by a stretchy spring, as shown in Figure 4.3. If the satellite travels in a slightly lower orbit, the satellite will move faster than the shuttle. This will increase the tension in the spring and result in a "drag" on the satellite. Normally if there is drag on a moving object, it will slow down. In the case of an orbiting satellite, however, the drag of the spring that slows the satellite leaves it with too little speed to maintain its orbit. The satellite must settle into a lower orbit where gravity is stronger and things orbit with even higher velocity. The net effect of the drag by the spring is to make the satellite settle into a lower orbit, closer to the Earth, where it moves even faster! This is yet another example of the working of conservation of energy (and angular momentum) when gravity is present. When a gravitating system loses energy, it heats up (like a star) or moves faster (like the satellite). When the satellite settles inward, it gains an even larger relative velocity with respect to the shuttle. The satellite will thus move even farther from the shuttle, increasing the tension in the spring and increasing the drag even more. The process clearly runs away, until the satellite burns up or crashes into the Earth or the spring breaks. In accretion disks, the shuttle and the satellite are represented by two blobs of matter in different orbits, and the spring depicts a line of magnetic force connecting them, as illustrated in Figure 4.4. Any attempt to connect the blobs by means of the magnetic field will cause them to orbit even farther apart and increase the tension in the magnetic field until it snaps. The snapping magnetic field can put energy into the roiling matter and drive the turbulent motions that make the friction and heat.

This magnetic coupling process must exist in accretion disks and play a role in their friction. It may not be the whole story because this theory does not seem to account for the full variability of the friction deduced from observations of accretion disks. Other theories propose that dynamos that generate magnetic fields spontaneously arise in the disk. Energy from the orbiting stars powers the dynamos. Eventual understanding will probably combine both of these ideas and more.

5. A Life of Its Own

One of the most compelling pieces of evidence that an accretion disk can have its own behavior is when a disk flares with increased brightness. In most systems, the matter flows from the companion star so rapidly that the accretion disk is kept hot and ionized, and the disk radiates steadily. In other systems, however, the flow of matter being transferred is not sufficient to keep the disk in the hot, bright state, and the disk flares only occasionally. Astronomers observe this behavior in disks around white dwarfs, neutron stars, and black holes. There may be a variety of phenomena involved in this flaring, but there is one process that certainly happens in common circumstances. Under certain conditions, the flow of matter in the disk cannot be steady. Rather, the matter stores and then flushes from the disk. The flushing stage is especially bright and causes the flare of radiation. This process is rather independent of the two stars that feed the disk and hold it together. The timing of the flare events and their specific observational features do depend on the central star. If the central star is a white dwarf, astronomers call the flaring a *dwarf nova* (Chapter 5). If the central star is a neutron star or black hole, the flushing of the disk results in an *X-ray transient* (Chapters 8 and 10).

The theory behind this behavior is that the generation of the friction and heating in the disk depends on the temperature in the disk. When the disk is at a low temperature, less than that at the surface of the Sun, the matter in the disk is rather transparent. Any heat generated by the low friction can easily escape as radiation, thus maintaining the low-temperature state. In this low-friction state, there is little tendency for the matter to settle inward, but new matter flows from the companion star. The addition of matter increases the density of the material in the disk. As the density increases, however, the matter becomes more opaque, radiation cannot escape so easily, and the temperature must rise. This leads to a runaway process. The reason is that, as the matter heats, it becomes even more opaque to radiation. This traps more heat, leading to a greater opacity and an even greater trapping of the heat.

The result is that the disk can exist in a cool, barely accreting state, with low luminosity, until enough density accumulates to trigger this heating runaway. The beginning of such an outburst is illustrated in the top two panels of Figure 4.5. A wave of heating runs through the disk. The wave can begin on the outside of the disk, as shown in the second panel of Figure 4.5, or deeper down in the disk, depending on circumstances. The disk suddenly becomes very hot and very bright. The disk reaches maximum brightness when the heating fully envelopes the disk as shown in the middle panel of Figure 4.5. The friction increases dramatically in the hot state, and so material that had accumulated in the outer parts of the disk rapidly moves inward. Ironically, this motion of the matter in the disk shuts the process off. As the outer portions of the disk thin out, they become more transparent again. They can radiate more easily, lose their heat, and lower the temperature. Now the inverse process sets in. As the temperature drops, the material becomes less opaque and more transparent, and this leads to a greater loss of heat, lower temperature, more transparency, and even greater loss of heat. A wave of cooling sets in from the outer parts of the disk that thin out first. This is illustrated in the fourth panel of Figure 4.5. The cool front sweeps inward, causing the majority of the matter in the disk to settle back into the cool storage state, as shown in the last panel of Figure 4.5. After an interval of storage, the cycle will then repeat.

The net effect is that the disk can exist in its cool storage state for a considerable time. The amount of time depends on circumstances, but the interval can vary from weeks to decades. The disk may be essentially undetectable during this phase. Then the eruption occurs, and the disk becomes very hot and bright for a short time, typically one-tenth the time the disk was dim, and is readily visible to astronomers. No sooner has the eruption occurred, however, than the disk starts to cool. Astronomers who want to study this transient bright phase must scramble!

An important aspect of this cycle of quiescence and eruption is that the process can be quite independent of the stars in the system. During the whole process, the mass-losing star can be pumping matter in at a perfectly constant rate. The star around which the accretion disk swirls provides a constant gravity. The flaring activity is a feature of the disk alone. In more complex systems, the mass can flow from the mass-losing star at a variable rate. The mass-gaining star can have a hard surface or strong magnetic field of its own (in the case of either neutron stars or white dwarfs). Either of these situations can lead to interesting variations.

6. Not So Flat, Buddy!

Another important idea has emerged in the last few years. The inner parts of accretion disks may not be so flat. Under certain circumstances, as the disk cools after its heating episode, the density can get so low that interactions among the particles are rare, and the efficiency of radiation can drop. This again leads to a retention of heat. The excess heat leads to pressure that causes the disk to swell up and become fatter, as shown in Figure 4.6. If this happens, this portion of the disk can become so hot that matter and antimatter, electrons and positrons, are created. The disk assumes a more nearly spherical configuration, and matter falls inward on the central star almost uniformly from all directions.

Under these circumstances, the matter can fall in so rapidly that the flow of matter carries the heat generated into the central star before the energy radiates away. This is especially true if the central star is a black hole. The heat energy disappears into the black hole just as the matter itself does. The result is that this fat, inner portion of an accretion disk is especially dim. What little energy leaks out corresponds to especially high energy radiation – high-energy X-rays and gamma rays. There is growing evidence that such regions do form in the centers of accretion disks as they settle back into their storage state. We will discuss this evidence in Chapter 10. One of the outstanding issues, the subject of current research, is when, why, and how a disk makes the transition from the relatively cool, flat configuration of a standard accretion disk to the very hot, fat configuration. Understanding this transition may give new clues for how to find and study black holes.