On masses of accretion disks in Type Ia supernova progenitors

A. V. Zhiglo

NSC Kharkov Institute of Physics and Technology, 1 Akademicheskaya str, Kharkov, 61108, Ukraine.

E-mail: azhiglo@kipt.kharkov.ua

Recent explanation [1] of high-velocity features in type Ia supernovae (SNIa) requires significant mass of circumstellar material (CSM) in SNIa progenitor system. If correct, it provides means of determining the mass of CSM along the line of sight. We study the distribution of mass in accretion disk, a natural candidate for the needed CSM. Accurate equation of state and Rosseland-mean opacities are used; several models for the latter are compared. We conclude that the standard model of accretion disk in SNIa progenitors does not yield the needed mass distribution to agree with observations.

Keywords: accretion disk, supernova, circumstellar matter, radiative transfer, opacity.

1 Introduction

Circumstellar accretion disks (AD) have been subject of active research since 1970s. The ones accreting onto compact stars are observed via characteristic X-ray radiation from the hottest inner region (where the plasma temperature reaches millions K, in the disks around neutron stars and black holes [2]). Parts of the disk with larger radial distance $r$ from the central star contribute less to the radiation; these farther parts in larger disks (beyond $R_\odot$, a solar radius, $\sim 10^{11}$ cm; where the temperature drops to $< 10^4$K) remained invisible despite containing most of the disk mass. In 2004 however there appeared a model [1] of the nature of high-velocity features (HVF) in the spectra of type Ia supernovae (SNIa), that in part provided means of estimating the mass of the circumstellar material (CSM) along the line of sight; AD is believed a major part of that CSM. The phenomenon behind HVF could suggest secondary parameters in SNIa observed data, helping to constrain their absolute brightness, which is desperately needed for cosmology (to improve the accuracy of distance measurements based on SNIa).

HVF were first identified in a CaII infrared triplet near 800 nm, seen near maximum light, blueshifted at velocities $\sim 17 000 - 29 000$ km s$^{-1}$, higher than the expansion velocity of the photosphere of the SN Ia ejecta ($\approx 11 000$ km s$^{-1}$). Similar HVF are sometimes seen in other lines (OI, MgII, TiII), harder to observe due to blending with background spectrum. HVF are now considered ubiquitous [3, 4]. The model [1] explains HVF as emission from a shell formed from CSM and outermost SN Ia ejecta as the former is overrun by the latter. The CSM is assumed of standard solar composition; calculations predict CaII triplet as the most pronounced spectral feature due to the shell. The model predicts a cutoff of (characteristic for SNIa) SiII lines in velocity space, at the same velocity as the Doppler-shift velocity of HVF; this was really observed [4]. Accretion disk (AD) is always present around the white dwarf (WD) before its explosion as SNIa in a single-degenerate scenario of SNIa (in which SNIa is a result of thermonuclear explosion of a WD [5] that reached nearly Chandrasekhar mass $M \approx 0.99M_{\odot}$ $\approx 1.37M_{\odot}$ by accreting mass from a companion star, through Roche lobe overflow. AD is currently considered the most likely candidate of the CSM needed for the HVF model.

In the model above the mass of the shell can be determined kinematically: the Doppler shift velocity of HVF is roughly estimated from momentum conservation in SNIa ejecta – CSM collision. This mass was found $5 \div 7 \times 10^{-3}M_\odot$ for SN 2005cg [4], $\sim 0.02M_\odot$ for SN 2003du [1], $0.2M_\odot$ for SN 2005hk [6]; the model [1] compared well with observations. Large fraction of this shell mass originates from the CSM located in the vicinity of the SN Ia center, at distances $< 1.5 \times 10^{15}$ cm (from HVF timing considerations).

In case the shell is not spherical the above estimates are for imaginary spherically-symmetric shell with the same angular mass density as in the actual shell along the line of sight (LoS) towards the observer. If most of the shell is made of the material of an axially symmetric AD with angular mass density $dm/d\theta$ the inferred spherical shell mass would be $m_{sph} = 2dm/(\cos \theta d\theta)$ for the LoS forming angle $\theta$ with the AD equatorial plane (EP). Thus the inferred shell mass for the same AD will appear larger than its total mass $m_{AD}$ if watched at close to its equatorial plane (along which most of the mass is concentrated), and almost no mass will be seen if watched from the polar direction. This assumes no significant mass redistribution takes place in the AD between the explosion and getting hit (supersonically) by the dense layers of the ejecta. We show below that the total mass of AD is $< 10^{-3}M_\odot$ for the currently accepted models of SNIa progenitor, however the inferred mass along LoS at $\theta = 0$ could...
reach $\sim 10^{-2} M_\odot$ under extreme parameter values with a red giant (RG) companion of the pre-explosion WD.

In this paper we study angular and radial distribution of mass in circumstellar disks, with parameters typical of the progenitor of SN Ia system. These are characterized by high accretion rate and relatively small size of the hot envelope of burning H on the WD ($R_{\text{env}} \lesssim 0.1 R_\odot$), which turns out shielded for outer AD by the bump at $r \approx 10^{11}$ cm on the disk. We therefore neglect AD irradiation by the WD, and find temperatures falling below $10^3 K$ at $r > 1 AU = 1.5 \times 10^{13}$ cm. We compare several prescriptions for AD opacity (dust-dominated) at these low temperatures [7, 8], as well as several compositions of AD. Of the 3 SN Ia progenitor channels (in single-degenerate model: the progenitor of SN Ia system. These are characterized by high accretion rate and relatively small size of the hot envelope of burning H on the WD, and angular rotation around the central object (WD in our case), $v_r \ll \omega r$. Radial pressure gradients can be neglected, angular velocities are close to Keplerian at the given radial coordinate $r$ of each AD element (AD matter is loosely called “gas”; in reality it may be ionized, or contain solid grains). Vertical (in $z$-direction) pressure gradient is due to vertical component of the WD gravity, $dP/dz = -\rho g_z = -\rho GM(z/r^2 + z^2)^{-3/2}$; thermal motion (with temperature $T(r, z)$) keeps the gas from settling to equatorial plane. We assume the dust (when present) having the same $T(r, z)$ and the same vertical distribution as the gas.

Parameter $\alpha$ of $\alpha$-disk model defines effective kinematic viscosity coefficient, $\nu = \alpha c_s H$, where $c_s$ is the sound speed in the disk material, $H$ is a characteristic scale height of the disk. This prescription assumes that characteristic turbulent velocity is $\alpha c_s$, and characteristic turbulent eddy size is of order $H$. In original formulation [2] the vertical structure of AD (i.e. distribution of density $\rho$, pressure $P$, temperature $T$, heat flux $F$, etc. along vertical, $z$-direction) was not studied in detail. Rough estimate $H = c_s/\omega$ was made, where $\omega$ is the Keplerian angular velocity at a given radius $r$ in the disk. We use $\nu = \alpha P/(\rho \omega)$ in this work, the prescription used most often. For circumstellar disks around compact stars $\alpha \in [0.01; 0.1]$ is normally used, as inferred from observations. For protoplanetary disks, conditions in which resemble those in ADs we study at $r \gtrsim 1 AU$ (except accretion rate $\dot{M}$), $\alpha = 0.01$ is considered appropriate [10]: smaller $\alpha$’s are used some times. We use $\alpha = 0.035$ as a base value in this work; when different $\alpha$’s are used that is mentioned explicitly.

The heat released due to viscous friction in the differentially rotating disk is the only heat source we consider; the (vertical) heat flux $F$ satisfies

$$dF = \frac{9 GM \nu \rho}{4 \cdot r^3};$$

radial heat flux is neglected in thin disks considered (all effects $\sim (z/r)^2$ are neglected). The heat is transported mainly by radiation and convection towards the disk photosphere, and is radiated into space. We solve exactly for the temperature gradient needed for transporting $F$ in the upper radiative region of AD [11], in gray atmosphere approximation. Unsöld convection prescription is used for getting $T(z)$ iteratively at each $r$. At large optical depth $1 \ll \tau(z) \equiv \int_{-\infty}^z \kappa \rho dz$ this simplifies to diffusion approximation often used

$$\frac{dT}{dz}_{\text{rad}} = \frac{-3 \kappa \rho F}{16 \sigma_{SB} T_\odot^4},$$

$\sigma_{SB}$ being the Stefan-Boltzmann constant.

Rosseland mean opacity $\kappa$ is used in our calculations; solving full frequency-dependent radiative transfer equations is known to not change the results much when the disk is not irradiated by external sources [12]. In the regions where the so found pure radiative $dT/dz$ exceeds adiabatic gradient Chandrasekhar instability drives convection, which becomes the main channel of heat transfer in such convective regions; we set convective temperature gradient in such regions as

$$\frac{dT}{dz}_{\text{conv}} = -\gamma_2 g z \rho T / P; \ \gamma_2 = \frac{\partial \ln T}{\partial \ln P} |_{\text{S}}.$$

Rosseland mean opacities are taken from [7, 13] for disks of solar composition [15]. At temperatures $< 1500 K$ solid grains that condense become the main absorber; several differing opacities are used by different groups at temperatures this low. To see how different opacities would change the results we perform some of the computations with low-$T$ opacities taken from [8]. Equation of state (EOS), determining $\rho$ and $\gamma_2$ for given $\{P, T\}$ is taken from [14].

We solve numerically for each $r$ a boundary-value problem for equations above with boundary conditions:

$F|_{z=0} = 0$; $F|_{z=z_0} = F_0 = \frac{9 \sigma_{SB} M_c}{4 \pi r^2}$ values for $P_{z=z_0}$ and $T_{z=z_0}$ consistent with $F_0$ and $\tau_{z=z_0} = \tau_0$ (found iteratively). $\tau_0$ was fixed at $10^{-5}$, $z_0$ was found by requiring $F|_{z=0} = 0$ when integrating from $z_0$ towards $z = 0$.

3 Results

The results are shown in the figures below. Quantities varied were a) viscosity parameter $\alpha$, shown $\alpha \in [0.002; 0.14]$; b) accretion rate $\dot{M} \in [4 \times 10^{-5}; 2 \times 10^{-4}] M_\odot \text{yr}^{-1}$ (also called $dM/dt$ or $\dot{M}$ in the graphs), that covers (still controversial) rates typical of SN Ia...
progenitors [16–18]; c) AD composition: mutual proportions of metals were kept solar [15], but the proportions between H, He and metals were changed for hands-on interpretation of the features in the disk structure, and for a feel of the effect of composition variations (for instance, for a He star as the companion). AD self-gravity is neglected (as $m_{AD} < 0.01 M_\odot$ is found); as is the effect of the companion for the most part. The accretor (WD) mass is taken $M = 1.37 M_\odot$.

Figure 1: Integral slope of AD photosphere $z_\tau/r$, at $\dot{M} = 10^{-6} M_\odot$ yr$^{-1}$ and varied $\alpha$.

Figure 2: Half surface mass density of AD, $1/2 \int_\infty^r \rho(r,z) dz$ vs radius $r$, at $\dot{M} = 10^{-6} M_\odot$ yr$^{-1}$.

Fig. 1 shows the profile of AD photosphere $z_\tau$ (at which optical depth $\tau = 2/3$), for solar composition AD (mass fraction of hydrogen X=0.7, that of metals Z=0.02, rest is helium, Y=0.28). $z_\tau$ is plotted divided by $r$; $z_\tau/r = const$ would correspond to the conical disk shape. The inner thick disk region ($r < 2 \times 10^9$ cm for base parameter values) is radiation pressure dominated. The disk is convective through most of its volume at $r < 5 \times 10^9$ cm: 5 more bands in $r$ are observed at larger $r$ in which the disk is convective. Transitions between radiative and convective zones, as well as sharp changes in $z_\tau(r)$ and surface mass density $dm/dS(r)$ shown in Fig. 2, occur in the regions where abrupt chemical or phase transformations take place, leading to abrupt changes in EOS (in inner disk) and opacity. The dip after $r \approx 1.2 \times 10^{11}$ cm is due to HeIII recombining into HeII, as may be seen from equatorial temperature profile in Fig. 3. Fig. 4 shows $z_\tau(r)$ at varied AD composition, and two models for low-temperature opacity [7, 8]. The dip is seen to be located at the same $r$ for the disks differing only in metallicity (Z).

Figure 3: Equatorial temperature and half-mass of AD at $\dot{M} = 10^{-6} M_\odot$ yr$^{-1}$. $T(z_\tau)$ is independent of $\alpha$.

Figure 4: $z_\tau(r)/r$ at $\alpha = 0.07$, varied AD composition. $\dot{M} = 10^{-6} M_\odot$ yr$^{-1}$ except the last 2 curves. At low temperature ($T < 10^4$ K) opacities [7] were used, except the curves labeled 'Semenov', for which $\kappa$’s were taken from [8].

The disk becomes radiative again at $r \approx 3 \times 10^{12}$ cm after the broad region where H and He recombine and $H_2$ molecules form. The temperature at which this transition occurs is $\approx 2000$ K (see Fig. 3), opacity increases rapidly (due to $H_2O$ molecules becoming the major absorber [7]) as can be seen in Fig. 5. At larger radii the photosphere slope $z_\tau/r$ regains about a half of its value at the bump prior to the dip at $r \approx 1.2 \times 10^{11}$ cm, however the WD stays shadowed by that bump for the outer disk region. Therefore we did not take irradiation by the WD into account; it would start affecting the disk structure at $r > 10^{13}$ cm, at smaller distances from the WD viscous heat in AD dominates over external irradiation heating. At very large radii however irradiation by the WD light scattered in the disk halo, and by the companion star become important, thus our model becomes deficient. Irradiation is known (see e.g. [10]) to increase $z_\tau$, at the same time decreasing $dm/dS$. Thus we expect our
A. V. Zhiglo. On masses of accretion disks in Type Ia supernova progenitors

model to overestimate AD mass in its outer regions.

Figure 5: Opacity (in units cm$^2$ g$^{-1}$) averaged over gas mass in radiative zone(s) at each r. Same $\alpha, M$, compositions and opacities used as in Fig. 4.

Figure 6: Equatorial temperature and half-mass of AD for the same models as in Fig. 4.

AD mass as a function of r, and equatorial temperatures for disks of different compositions or opacities is shown in Fig. 6. The mass gets larger for less opaque disks (with lower fraction of H or metals) than for the base model (of solar composition, with [7, 13] opacities). More accurate study is however required in outer optically thin regions of AD: optical depth $\tau(z=0)$ drops to < 0.1 for both models with $Z = 0$ at $r > 10^{12}$ cm. $z_r/r$ drops rapidly with r in this regime, making the mass more concentrated near EP, conflicting with anisotropy in HVF observed not very pronounced [19]. $\tau(z=0)$ stays > 10 for the base model at all $r < 10^{15}$ cm. $dm/dS$ and $z_r$ increase with $M$; however our base $M = 10^{-6} M_\odot$ yr$^{-1}$ is near its maximum value allowing for mass loss from the companion actually increasing the WD mass [16-18]. The gravity of the companion could lead to a more massive AD. Fig. 7 shows the density distribution, seen grossly affected by the companion.

The density next to EP is however affected to a smaller degree, and effect on $dm/dS$ is nearly unnoticeable up to distances a few percent from the companion center.

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure5.png}
\caption{Opacity (in units cm$^2$ g$^{-1}$) averaged over gas mass in radiative zone(s) at each r. Same $\alpha, M$, compositions and opacities used as in Fig. 4.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure6.png}
\caption{Equatorial temperature and half-mass of AD for the same models as in Fig. 4.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure7.png}
\caption{Density in AD of base model with 4 $M_\odot$ companion 6.02 $\times 10^{13}$ cm away from the WD.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure8.png}
\caption{Angular mass distribution. Angle $\theta$ of the line-of-sight is measured from the disk equatorial plane. Five sets of disk parameters are shown, differing in $M$, indicated in the legend at the respective curve (in units of $M_\odot$ yr$^{-1}$.) The group labeled “$1e-6a$” corresponds to $M = 10^{-6}$, $\alpha = 0.0045$; in the rest of the models $\alpha = 0.035$. 3 curves are shown per each model, for disk radii $1.55 \times 10^{13}$, $1.55 \times 10^{13}$ and $6.17 \times 10^{13}$ cm. Smaller radii correspond to lower curves.

The interstellar distance $a$ in Fig. 7 is taken $\approx 6 \times 10^{13}$ cm, i.e. about the maximal radius RG can have; its mass was also taken near its maximal value in a SNIa progenitor. Actual disk outer radius is usually about $a/5$, so no companion effect on the disk mass is expected.

Fig. 8 shows angular mass distribution, for 3 radii chosen (smallest one may correspond to a real disk in SNIa progenitor with very large MS or subgiant companion, $r = 1.55 \times 10^{13}$ cm is about the disk radius expected in a binary with the largest possible RG). In Fig. 9 $dm/d\theta(\theta=0)$ is plotted as a function of $r$ for a range of $\alpha$’s and $M$. Equivalent spherical CSM mass $m_c(\theta) = 2dm/d\theta/\cos \theta$ (approximately twice the quantity shown at the ordinate axes) is seen to vary in $[4 \times 10^{-3}, 9 \times 10^{-2}] M_\odot$ for AD parameters shown at $\theta = 0$, about the right range to explain HVF observations, at $r_{AD} \approx 1$ AU. However, anisotropy of the mass distribution conflicts with observations [19].

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure9.png}
\caption{Angular mass distribution. Angle $\theta$ of the line-of-sight is measured from the disk equatorial plane. Five sets of disk parameters are shown, differing in $M$, indicated in the legend at the respective curve (in units of $M_\odot$ yr$^{-1}$.) The group labeled “$1e-6a$” corresponds to $M = 10^{-6}$, $\alpha = 0.0045$; in the rest of the models $\alpha = 0.035$. 3 curves are shown per each model, for disk radii $1.55 \times 10^{13}$, $1.55 \times 10^{13}$ and $6.17 \times 10^{13}$ cm. Smaller radii correspond to lower curves.

The interstellar distance $a$ in Fig. 7 is taken $\approx 6 \times 10^{13}$ cm, i.e. about the maximal radius RG can have; its mass was also taken near its maximal value in a SNIa progenitor. Actual disk outer radius is usually about $a/5$, so no companion effect on the disk mass is expected.

Fig. 8 shows angular mass distribution, for 3 radii chosen (smallest one may correspond to a real disk in SNIa progenitor with very large MS or subgiant companion, $r = 1.55 \times 10^{13}$ cm is about the disk radius expected in a binary with the largest possible RG). In Fig. 9 $dm/d\theta(\theta=0)$ is plotted as a function of $r$ for a range of $\alpha$’s and $M$. Equivalent spherical CSM mass $m_c(\theta) = 2dm/d\theta/\cos \theta$ (approximately twice the quantity shown at the ordinate axes) is seen to vary in $[4 \times 10^{-3}, 9 \times 10^{-2}] M_\odot$ for AD parameters shown at $\theta = 0$, about the right range to explain HVF observations, at $r_{AD} \approx 1$ AU. However, anisotropy of the mass distribution conflicts with observations [19].
Figure 9: $d\theta/d\theta$ at $\theta = 0$ as a function of radius. Note that to get an inferred CSM mass of $10^{-2}M_\odot$ the disk radius must exceed $10^{12}$ cm even at very low $\alpha = 0.0022$. For the base model we study ($\alpha = 0.035, M = 10^{-6}$) the disk radius should be $10^{13}$ cm, only possible with the largest RG companions.

4 Conclusions

We studied possible masses of AD in SNIa progenitors, and the spatial distribution of the mass. The work was inspired by a model of HVF in SNIa [1], requiring a few percent of $M_\odot$ of CSM universally present in the immediate vicinity ($r \lesssim 10^{15}$ cm) of the exploding WD. We used accurate EOS and opacities of AD matter, used in stellar modelling, which led to a prediction of certain features of the disk structure, in particular a bump at $r \approx 10^{11}$ cm shielding the outer disk from the WD radiation. A few simplifications made deserve further study and can change the results. These are simple treatment of convection and viscosity, gray radiative transfer, neglecting irradiation of the outer disk from the disk halo and the companion, possible dust settling. The main conclusion however is robust, namely that the HVF model [1] with AD as the principal ingredient of CSM conflicts with observations. We saw that AD in a WD + MS progenitor does not contain enough mass even in the direction of its equatorial plane, at $\alpha$’s as small as 0.001 and $M$ up to $2 \times 10^{-6} M_\odot$ yr$^{-1}$, by a large margin, a factor $\sim 10^{3}$. Only progenitors with largest RG companions may have sufficient mass; these constitute a minority in progenitors population, contradicting the universality of HVF [3, 4], as well as facing difficulties in explaining only mild anisotropy ($\sim 40\%$) in HVF [19]. Either different CSM source should exist (e.g. a common envelope), or the HVF model is incorrect, or at least not the whole picture.

I am grateful to Yu.L. Bolotin for computer resources, to J.W. Ferguson for comments and references. This research was partly supported by RFFD grant # F40/14-2012.

References

А. В. Жигло

О МАССАХ АККРЕЦИОННЫХ ДИСКОВ В ПРЕДШЕСТВЕННИКАХ СВЕРХНОВЫХ ТИПА Ia

Недавнее объяснение [1] высокоскоростных особенностей в сверхновых типа Ia (СН Ia) требует значительной массы околозвездного вещества (ОЗВ) в системе предшественника СН Ia. Если верно, это объяснение предоставляет возможность определения массы ОЗВ вдоль луча зрения. Мы изучаем распределение массы в аккреционном диске, естественным образом ОЗВ. Используется детальное уравнение состояния и Рессельовские средние коэффициенты рассеяния излучения; для последних сравниваются несколько моделей. Мы заключаем, что распределение массы в аккреционных дисках, согласно их стандартной модели, не согласуется с наблюдениями.

Ключевые слова: аккреционный диск, сверхновые, околозвездное вещество, перенос излучения, непрозрачность.

Жигло А. В., кандидат физико-математических наук, младший научный сотрудник.
Харьковский физико-технический институт НАН Украины.
ул. Академическая, 1, Харьков, Украина, 61108.
E-mail: azhiglo@kpi.kharkiv.ua