Asymmetry of $^{56}$Ni ejecta and polarization in type IIP supernova 2004dj

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ABSTRACT

I study a problem, whether the asymmetry of a $^{56}$Ni ejecta that results in the asymmetry of the H$\alpha$ emission line at the nebular epoch of the type IIP supernova SN 2004dj is able also to account for the recently detected polarization of the supernova radiation. I developed a model of the H$\alpha$ profile and luminosity with a nonthermal ionization and excitation taken into account adopting an asymmetric bipolar $^{56}$Ni distribution. On the background of the recovered distribution of the electron density I calculated the polarized radiation transfer. It is demonstrated that the observed polarization is reproduced at the nebular epoch around day 140 for the same parameters of the envelope and $^{56}$Ni distribution for which the luminosity and profile of H$\alpha$ are explained. Yet the model polarization decreases slower compared to observations. The origin of an additional component responsible for the early polarization on day 107 is discussed.

1. Introduction

A problem of an explosion mechanism for type II supernovae remains unresolved, although this phenomenon is undoubtedly related with the gravitational collapse of an iron core. In this regard of great importance are the observational manifestations of the explosion that might hint the ways of the problem solution and to play a role of observational tests of models. One of the specific properties of the explosion mechanism is the asymmetry (Ardelean et al. 2005; Blinnikov et al. 1990; Herant et al. 1992; Scheck et al. 2004; Burrows et al. 2005). It can manifest itself both in the asymmetry of the emission line profiles and in the polarization of radiation. Asymmetry effects were observed for the first time in the anomalous type IIP supernova SN 1987A (for H$\alpha$ asymmetry see Phillips and Williams [1991] and for the polarization see Jeffery [1991]). Both effects have been interpreted in a model of asymmetric $^{56}$Ni ejecta embedded in the symmetric envelope (Chugai 1991, 1992). The line asymmetry was observed also in the normal type IIP supernova SN 1999em (Elmhamdi et al. 2003). Interestingly, in both supernovae the asymmetry was characterized by the redshift which indicated that the $^{56}$Ni was ejected predominantly toward the far hemisphere.
A standard type IIP supernova SN 2004dj (Nakano et al. 2004) generated a great interest because of its proximity (D=3.13 Mpc). However, more important is that its nebular spectra revealed a strong line asymmetry, particularly of the Hα emission. The asymmetry manifested itself as a pronounced blueshift of emission line maximum by about 1500 km s\(^{-1}\) (Chugai et al. 2005). Modeling the Hα in that paper led us to conclude that \(^{56}\)Ni is distributed as bipolar asymmetric ejecta with a more massive jet residing in the near hemisphere.

The recovery of the \(^{56}\)Ni distribution upon the basis of the profile modeling is, strictly speaking, ill-posed problem, so doubts may arise whether this procedure is unambiguous. An independent confirmation is therefore needed. Recently Leonard et al. (2006) reported results of the polarimetric observations of SN 2004dj in which the intrinsic variable polarization in the band of 6800 – 8200 Å was detected with maximum value of 0.56% at the end of the light curve plateau. According to authors suggestion the polarization in SN 2004dj arises because of the Thomson scattering, while the evolution of the polarization is interpreted as a result of the decrease of the Thomson optical depth of the supernovae with spherical envelope and asymmetric core. It is shown, simultaneously, that the change of position angle of the polarization contradicts to the model of axially symmetric bipolar \(^{56}\)Ni ejecta.

A question arises whether the asymmetry of the \(^{56}\)Ni distribution responsible for the Hα profile asymmetry of the SN 2004dj is able also to account for the polarization at least at the nebular epoch? The present paper is concentrated on the answer to this important question. In second section I describe the model used to compute the electron density distribution caused by the asymmetric \(^{56}\)Ni distribution. The third section presents results of the modelling of Hα line and of the polarization produced by the Thomson scattering of continuum photons in the asymmetric electron distribution.

I adopt 2004 June 28 to be the explosion date in contrast to June 13 adopted in the previous paper. The revision is dictated by two arguments. First, plateau length of SN 1999gi, which was used as a template for SN 2004dj, is maximum (≈ 125 d) among type IIP supernovae, while the average duration is ≈ 110 d. Second, from the spectral evolution of SN 2004dj Patat et al. (2004) estimate the explosion date to be about July 14. Adopting the plateau duration to be 110 d we come to a compromise explosion date of June 28, which is two days earlier than the explosion date estimated by Vinko et al. (2006) from the analysis of the photosphere evolution.
2. Model of SN 2004dj asymmetry

The calculation of the intrinsic polarization of SN 2004dj at the nebular epoch is reduced to the calculation of (a) the deposition of the gamma-rays of $^{56}$Co--$^{56}$Fe decay; (b) ionization balance of the hydrogen for the adopted spherical density distribution and asymmetric $^{56}$Ni distribution; (c) transfer of the polarized radiation on the background of the asymmetric distribution of the electron density. The optimal parameter choice of the $^{56}$Ni distribution is determined from the description of the Hα profile and luminosity. It should be emphasised that unlike the previous model, in which the Hα emissivity was assumed to be proportional to the deposition, here I calculate the hydrogen ionization and Hα emissivity in more detail.

The adopted model of the SN 2004dj envelope and $^{56}$Ni distribution, repeats, with minor exceptions, the model used previously for the Hα profile calculation (Chugai et al. 2005). Specifically, the $^{56}$Ni distribution is represented by the central component and bipolar jets. Note, here the central $^{56}$Ni component is a complete sphere (Fig. 1), not cut sphere as previously assumed (Chugai et al. 2005). The envelope expands homologously, i.e., the velocity, radius and age obey the relation $v = r/t$. The envelope is spherically-symmetric (with the exception of $^{56}$Ni) and the density-velocity dependence is exponential $\rho = \rho_0 \exp(-v/v_0)$, where $\rho_0 \propto t^{-3}$ and $v_0$ are determined by the kinetic energy $E$ and mass $M$. The exponential law qualitatively reproduces the density distribution of hydrodynamical models in the relevant velocity range $v \leq 5000$ km s$^{-1}$. The hydrogen abundance in the envelope is $X = 0.7$. In the central zone $v < v_s$, which presumably coincides with the spherical $^{56}$Ni component, the hydrogen resides, presumably, in condensations with $X = 0.7$ and the volume filling factor $f < 1$. Note, in the previous paper the parameter $f$ was absent; instead it was assumed that $f$ linearly increased between zero and unity in the velocity range $0 < v < v_s$. Following the previous paper I assume here that $^{56}$Ni condensations are imbedded in the hydrogen-free cocoons with the total mass $M_c$. The justification and details of the model of the $^{56}$Ni distribution along with the method of the calculation of the gamma-ray deposition are given in the previous paper (Chugai et al. 2005).

The hydrogen ionization is calculated from equations of the ionization balance for two-level hydrogen atom with the continuum. In this approximation we are able to take into account major processes of the nonthermal ionization and excitation along with the photoionization due to the absorption of the two-photon and recombination Balmer continuum radiation from the second level (Chugai 1987; Xu et al. 1992). The radiation transfer in the Balmer continuum is treated using a local approximation. The absorption probability of the recombination Balmer continuum is set to be $w_2 = \tau_2/(1 + \tau_2)$. Here $\tau_2$ is the local optical depth parameter $\tau_2 = \sigma_2 n_2 v_0 t$, where $\sigma_2$ is the photoionization cross-section at the threshold, $n_2$ is the population at the second level, $v_0$ is the velocity scale of the exponential
density distribution. The absorption probability of the two-photon radiation is approximately 
\[ w_{2q} = \frac{\tau_2}{3 + \tau_2} \] given the frequency dependence of the cross-section \( \sigma \propto \nu^{-3} \) and the weak frequency dependence of the two-photon spectrum.

The total rate of the hydrogen nonthermal ionization and excitation is

\[ G = \epsilon (1 - \eta) \chi^{-1}, \quad (1) \]

where \( \epsilon \) (erg cm\(^{-3}\) s\(^{-1}\)) is the energy deposition rate, \( \chi \) is the hydrogen ionization potential, \( \eta \) is the energy fraction spent on the Coulomb heating, which, using calculations by Kozma and Fransson (1992), can be approximated as \( \eta = x^{0.24} \) (where \( x \) is the hydrogen ionization fraction). Strictly speaking, one needs to take into account that the deposition is shared between hydrogen and helium. However, since the ultraviolet photons emitted by helium owing to the nonthermal ionization and excitation efficiently ionize hydrogen, the omission of the nonthermal ionization of He does not markedly change the rate of hydrogen ionization and excitation compared with the approximation (1).

I assume following Xu et al. (1992) that the energy spent on the nonthermal hydrogen ionization and excitation is shared between the ionization with the branching ratio \( \phi_1 = 0.39 \), second level excitation \( (\phi_2 = 0.47) \) and third level excitation \( (\phi_3 = 0.14) \). Collisions with thermal electron are also taken into account. Since a thermal balance is not calculated I adopt the constant electron temperature \( T_e = 5000 \) K. The model with \( T_e = 4500 \) K produces only 5% lower emission measure, i.e., \( \sim 2.5\% \) lower electron concentration. This demonstrates a weak sensitivity to the electron temperature in the region of reasonable values of this parameter. Balance equations for the ionization and second level population with principal processes taken into account read

\[ G \phi_1 + n_2 (P_2 + q_2 n_e) + q_1 n_e n_1 = \alpha_B n_e^2, \quad (2) \]

\[ n_2 (A_{2q} + q_{21} n_e + A_{21} \beta_{12} + P_2 + q_2 n_e) = \alpha_B n_e^2 + G (1 - \phi_1) + q_{12} n_e n_1, \quad (3) \]

where \( P_2 \) is the photoionization rate for the second level, \( \alpha_B \) is the recombination coefficient for excited levels \( n \geq 2 \), \( n_e \) is the electron concentration, \( A_{2q} = 2.06 \) s\(^{-1}\) is the probability of the two-photon transition 2–1 (I assume the equipartition between 2s and 2p levels), \( q_{12}, q_{21} \) are the collisional excitation coefficients, \( q_1, q_2 \) are collisional ionization coefficients, \( A_{21} \) is the spontaneous transition rate, \( \beta_{12} \) is the Sobolev escape probability for the L\( \alpha \) photon. In equation (3) I adopt that the nonthermal excitation of the third level (second term in the right hand side) results in the excitation of the second level. The photoionization rate is determined by the absorption of the two-photon and recombination Balmer continuum radiation:

\[ n_2 P_2 = 1.42 n_2 A_{2q} w_{2q} + \alpha_2 n_e^2 w_2. \quad (4) \]
The factor 1.42 takes into account the fraction (0.71) of the two-photon radiation with energy > 3.4 eV and that two photons are emitted simultaneously.

Optimal parameters of the $^{56}$Ni distribution are chosen via modelling the Hα profile and its evolution. The Hα emissivity is calculated using the balance equation for the third level that includes the major processes: recombinations to levels $n \geq 3$, nonthermal excitation of the third level by fast electrons and de-excitation by thermal electron collisions. The net rate of the Hα emission (erg cm$^{-3}$ s$^{-1}$) is then

$$\epsilon_{32} = h\nu_{23}(\alpha_C n_e^2 + Gf_3 + q_{23}n_e n_1 + q_{13}n_e n_1) \frac{A_{32} \beta_{23}^3}{A_{32} \beta_{23}^3 + q_{32} n_e},$$

where $\alpha_C$ is the recombination coefficient to levels $n \geq 3$. The above equations of ionization and level populations balance are solved for the envelope with the kinetic energy of $E = 1.5 \times 10^{51}$ erg that is characteristic of SN 1987A (Utrobin 2005) and ejecta mass $M = 15 M_\odot$. The adopted $^{56}$Ni mass is 0.02 $M_\odot$ (Chugai et al. 2005). Our computations show a weak dependence on the energy. The model with lower energy, $E = 10^{51}$ erg being characteristic of SN 1999em (Baklanov et al. 2005) predicts practically the same Hα profile and the very small difference in the Hα absolute luminosity behavior.

The transfer of the polarized radiation of the quasi-continuum in the 7000—8000 Å band is modelled by Monte Carlo technique (Angel 1969). I consider only Thomson scattering of photons. The direction and polarization of the scattered photon is diced according to the dipole scattering law. Stokes vector components $I$, $Q$, and $U$ of escaping photons are summed in the corresponding polar angle bin. The number of photons in a typical simulation is $\sim 10^7$. The code was tested using available analytical results. In particular, the model reproduces the Chandrasekhar-Sobolev limit ($p = 11.7\%$) in the problem of the polarization for the Thomson scattering in the plane atmosphere.

### 3. Results

Calculations of the Hα profile and polarization were performed for the models with the inclination angle of the $^{56}$Ni ejecta $i = 30^\circ$ (model M1), likewise in the previous model (Chugai et al. 2005), and $i = 40^\circ$ (model M2). Parameters of the $^{56}$Ni distribution for all the models, including previous model M0 (Chugai et al. 2005), are given in Table 1. Starting with the third column the Table presents the expansion velocity of the central component, boundary velocities of jets in the near and far hemisphere, mass of the central $^{56}$Ni component, masses of both $^{56}$Ni jets, total mass of cocoons, and the volume filling factor $f$ of the hydrogen in the central zone (in the model M0 this parameter is absent). Parameters
of the model M1 are a bit different from those of the model M0 because the model M1 has a different geometry of the central component, the model M1 takes into account the filling factor, and the model describes sources of Hα photons in greater details.

Both M1 and M2 models sensibly reproduce the observed Hα luminosity (Fig. 2). This provides a confidence that the model includes essential processes of the hydrogen ionization and excitation in the envelope. Additional support for the model comes from a close similarity between calculated and observed Hα profiles for different moments (Fig. 3). This confirms the major result of the previous simulations performed in the frame of a more simple model M0. one should emphasise, however, that the absolute correspondence between model and observed profile is lacking. This indicates that the real supernova has, probably, more complicated structure than our model.

The polarization caused by the Thomson scattering is computed using the distribution of the electron concentration found from the modelling of the Hα profile. Isodensity lines for the electron concentration in the model M1 on days 116 and 315 are shown in Fig. 4. The hourglass structure on day 116 is due to the small (compared with radius) free path length of gamma-quanta in the inner region and large path length in the outer layers. With time the ne distribution gets more spherical because of the increase of the free path length of gamma-quanta. To compute the polarization we must also set the distribution of the photon sources. I follow a reasonable assumption that the emissivity of the quasicontinuum is proportional to the deposition rate $\epsilon$.

The polarization in model M1 and M2 on days 116 and 222 is shown in Fig. 5 as a function of cosine of the polar angle $\theta$ measured from the axis of the rotational symmetry. Both models result in the similar polarization for the same angles. However, for specific inclination angles of the models, i.e., $i = 30^\circ$ for M1 and $i = 40^\circ$ for M2, the polarization in the model M2 is significantly (1.5–2 times) larger than in the model M1. The polarization decline with time reflects both the decrease of the Thomson optical depth and spherization of the distribution of the electron concentration. Note, the position angle of the polarization vector in our model is perpendicular to the axis of the rotational symmetry.

It is instructive to calculate the polarization in the model M1Ni (Fig. 5) which differ from the model M1 by the larger $^{56}$Ni mass (0.075 $M_\odot$ versus 0.02 $M_\odot$). The $^{56}$Ni mass in the model M1Ni is equal to that found in SN 1987A. This calculation demonstrates the polarization for a hypothetical SN IIP with the $^{56}$Ni mass to be characteristic of SN 1987A and $^{56}$Ni asymmetry to be characteristic of SN 2004dj. Interestingly, the polarization for the inclination angle $i \sim 90^\circ$ in the model M1Ni is only by a factor of 1.44 larger than in the model M1. This means that the dependence of the polarization on the $^{56}$Ni mass is somewhat weaker than square root of the mass. The latter is expected in a naive model.
with the recombination rate to be proportional to the deposition rate. Let us compare
the computed polarization in the model M1Ni with the observed polarization of SN 1987A
at the nebular epoch. Around day 200 the intrinsic polarization of SN 1987A in $R$ band
(where effect of line scattering is small) is about $0.9 \pm 0.17\%$ (cf. Jeffery 1991). According
to the model M1Ni this value corresponds to the inclination angle of the bipolar ejecta
$i \sim 53 \pm 10^\circ$. This estimate should be regarded, of course, as illustrative. Yet, it is amazing
that the value coincides within errors with the inclination of the bipolar ejecta of SN 1987A
$i \approx 45^\circ$ estimated from different arguments (Wang et al. 2002).

I return now to the polarization evolution in SN 2004dj. The calculated polarization
in models M1 and M2 taking into account their inclination angles (Table 1) is shown in
Fig. 6 together with the observed polarization for SN 2004dj reported by Leonard et al.
(2006). The model M2 predicts too large polarization compared to observations and thus
should be discarded. The polarization in the model M1 reproduces the observed value on
day 144. However, the later decline of the model polarization is slower compared to the
observed polarization. This mismatch possibly stems from the model drawback responsible
for poor description of the central part of the $H\alpha$ profile on days 222 and 315 (Fig. 3). Our
model probably is not quite adequate in the description of the central zone structure, where
deviations from the bipolar structure are conceivable. Another drawback of the model is
somewhat lower polarization around day 110 compared to observational value (Fig. 6). The
inconsistency of the model at this epoch is, however, unavoidable by, at least, two reasons.

First, on day 107 the supernova is still at the photospheric stage, although at the
very end of it. At this epoch the thermal ionization is dominant, which makes our model
unapplicable. The role of the thermal ionization at that time is illustrated by Fig. 7 which
shows the $H\alpha$ line on days 107 (Leonard et al. 2006), 112, and 116 (Chugai et al. 2005).
On day 116, as we saw above (Fig. 3), the $H\alpha$ line is well described by the model of the
nonthermal ionization caused by the asymmetric bipolar $^{56}$Ni ejecta. A bit earlier, on day
112, the profile shows symmetric component related with the residual thermal ionization.
On day 107 the symmetric component related with the thermal ionization is dominant (Fig.
7). Our model thus is not applicable for the description of the polarization at this stage.

The second reason, why the model is not valid on day 107, is even more crucial. According
to polarization data (Leonard et al. 2006) the position angle (PA) of the polarization
vector is $28^\circ$, whereas for the next observation moment (144 d) and later on PA$\approx 178^\circ$.
Between days 107 and 144, thus, PA rapidly changes by $\approx 30^\circ$. The persistence of PA at the
nebular epoch is consistent with the model of the axisymmetric bipolar $^{56}$Ni ejecta, while
the observed change of PA at the early epoch, on the contrary, disagrees with this model.
Generally, the transition from optically thick to optically thin scattering regime may cause
a jump of PA of the polarization vector by 90° \citep{Angel1969}. This phenomenon, obviously, has nothing to do with the observed PA jump by \approx 30°. The behavior of PA between days 104 and 144 indicates, therefore, that some additional transient component of polarized radiation dominates around day 107 and this component is not related to axisymmetric $^{56}$Ni ejecta \citep{Leonard2006}. The early polarization component may be dubbed for clarity “photospheric” in contrast to the “nebular” at the epochs $t \geq 140$ d.

In the range of the applicability of the axysymmetric model ($t \geq 140$ d) one may claim that the model of the bipolar $^{56}$Ni ejecta with the inclination angle $i = 30°$ that describes the Hα profile also reproduces the observed polarization at the early nebular epoch ($t \sim 130–150$ d) and is consistent qualitatively with the subsequent polarization decrease. It should be emphasised, however, that at the late nebular epoch ($t \sim 200$ d) the theoretical polarization is somewhat higher than the observed one.

4. Conclusion

The primary goal of the paper was to provide an answer to the question whether the asymmetry of the $^{56}$Ni distribution responsible for the asymmetry of the Hα emission line at the nebular epoch of SN 2004dj is able to account for the observed polarization as well. I constructed a model of the Hα profile and luminosity with the nonthermal excitation and ionization of hydrogen for the asymmetric $^{56}$Ni distribution. I then calculated the transfer of a polarized radiation using Monte Carlo technique. The modelling shows that the model of the bipolar ejecta, which describes the Hα line, predicts that the model polarization is consistent with the observed polarization in SN 2004dj at the early nebular epoch. At the late stage $t \sim 200$ d the theoretical polarization is somewhat larger compared with observations. This disparity is possibly related with a more complicated structure of the matter distribution, including $^{56}$Ni, in the inner zone of the envelope.

The photospheric component of the polarization observed on day 107 is not described in principle by the model of the axisymmetric $^{56}$Ni ejecta. \citet{Leonard2006} attribute the early polarization to the deviation of the bipolar $^{56}$Ni ejecta from the axial symmetry. According to their conjecture the recombination wave propagating toward the center of the supernova envelope uncovers in sequence layers with different position angles of $^{56}$Ni clumps. This might explain the observed change of polarization position angle between days 107 and 144. In this model the photosphere plays a role of a homogeneous screen, while asymmetry arise from the enhanced ionization originated from the asymmetric $^{56}$Ni distribution. The scenario proposed by \citet{Leonard2006} can be dubbed “the model of non-axisymmetric $^{56}$Ni ejecta”.
An alternative conjecture that does not require abandoning the axial symmetry of $^{56}\text{Ni}$ ejecta is conceivable either. Note, the photospheric component of the polarization emerged at the phase when the photosphere almost reached the center of the supernova envelope. On the other hand, the distribution of the chemical abundance in the inner layers of supernova should be essentially inhomogeneous due to an incomplete mixing of the hydrogen and helium envelopes during the shock wave propagation (Müller et al. 1991). The photosphere that forms in the chemically inhomogeneous material unavoidably should acquire large scale brightness variations that might result in a significant polarization of the photospheric radiation. Such a scenario one may dub a model of "spotty photosphere" in contrast to the model of non-axysymmetric $^{56}\text{Ni}$ ejecta.

In both conjectures the early polarization is related to the final photospheric phase and in both mechanisms a "flash" of polarization should generally emerge at the end of the light curve plateau. The difference is that in the model of the spotty photosphere the polarization flash should be present even in SN IIP with the almost spherical $^{56}\text{Ni}$ distribution, while the model based on the $^{56}\text{Ni}$ asymmetry predicts in this case essentially weak/no polarization. This signature can be used to discriminate between alternative conjectures about the origin of the photospheric component of polarization in SN 2004dj and other SN IIP with the detected polarization flash.

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Table 1: Parameters of $^{56}$Ni distribution

| Model | $i$  | $v_s$ | $v_1$ | $v_2$ | $M_s$ | $M_1$ | $M_2$ | $M_c$ | $f$ |
|-------|-----|-------|-------|-------|-------|-------|-------|-------|-----|
|       |     | km s$^{-1}$ |       |       |       |       |       |       |      |
|       |     | $M_\odot$ |       |       |       |       |       |       |      |
| M1    | 30° | 1300  | 2600  | 3800  | 0.0078| 0.009 | 0.0032| 0.8   | 0.3 |
| M2    | 40° | 1250  | 3100  | 4500  | 0.0086| 0.0083| 0.0031| 0.9   | 0.4 |
| M0    | 30° | 1400  | 2700  | 3500  | 0.0078| 0.0083| 0.0038| 1.3   |     |
Fig. 1.— Schematic representation of the spherical envelope with bipolar $^{56}\text{Ni}$ ejecta inside. Nickel ejecta with the inclination angle $i$ consists of the central spherical component $S$ and two cylindrical jets (jet 1 is in near hemisphere).
Fig. 2.— Hα luminosity of SN 2004dj according to observations (squares) and models M1 and M2 (line).
Fig. 3.— Hα profile for different moments in the model M1 (thin solid line) and in the model M2 (thick solid line) as compared to observations (dotted line). The flux is in arbitrary units.
Fig. 4.— Isodensity lines of the electron concentration in meridional plane for the model M1 in two phases. The ordinate is the velocity along the axis of ejecta, the absciss is the velocity in a perpendicular direction. The concentration varies by a factor of two between neighbouring contours. The external contour corresponds to the concentration $10^6$ cm$^{-3}$. 
Fig. 5.— Polarization for two moments as a function of cosine of the polar angle for the model M1 (upper panel), M2 (middle panel), and M1Ni (lower panel)
Fig. 6.— Evolution of polarization in the models M1 and M2 compared with the observed polarization (filled circles).
Fig. 7.— Hα evolution between days 107 and 116 at the phase of the transition from the light curve plateau to the radioactive tail. The flux in maxima is normalized on the same value. The symmetric component of ionization apparently dominates on day 107 and then quickly fades during subsequent 9 days.