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Some peculiarities of spectropolarimetric observations of supernova stars

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Abstract. We present a short review of polarimetric observations of supernovae. The results of polarimetric observations of SN 2005 made by astronomers of Saint-Petersburg State University in the Crimea are presented. This supernova shows the highest degree of polarization measured in the optical bandpass. One of the discussed problem is the highest polarization value of the Type II-plateau SN 1999gi which cannot be explained by interstellar origin. We show that the electron scattering in the SN envelope with a dipole magnetic field is responsible for production of polarized radiation. Thus we have the first direct determination of magnetic field of SNe.

1 Introduction

Supernovae have been studied with modern scientific methods for more than a century. During this time, it has been traditional to assume that these catastrophic stellar explosions are spherically symmetric. This assumption has some reasons. Theoretical study of stellar explosion has been rather difficult even with this assumption of spherical symmetry. But the evidence of asphericity of supernovae explosions has been growing for years and especially at the last time.

A decisive tool for solving this problem is SN spectropolarimetry, an observational technique that allows the only direct test of the early time SN geometry. Namely, Shapiro and Sutherland (1982) were the first who pointed out that polarimetry of a young SN is a powerful tool for probing its geometry. Their idea was quite simple: a hot young SN atmospheres and envelopes are dominated by electron scattering, which by its nature is highly polarizing. It is possible to resolve an atmosphere itself if we would measure changes in both the polarization degree and position angle as a function of time. It is well known that if the source with dominated electron scattering is aspherical, incomplete cancellation of polarization patterns occurs, and a net polarization results (Filippenko and Leonard, 2003).

At the last time a lot of evidence has been accumulated that the net emission from core-collapse supernovae is often intrinsically polarized. For instance, $\sim 4\%$ polarization was observed from a Type Ic SN (Wang et al., 2001).

A bipolar jet model for supernova polarization was proposed by Jeffery (2004) and has been recently developed by Chugai (2006). The light from the main component of the supernova which may be called as a bulk scatters off electrons in the jets and is polarized. This polarized light is added to the direct emission from the bulk SN and produces the overall SN emission to be polarized. The main features of polarization that are qualitatively reproduced for some SNe are characterized by the rise to a polarization maximum and then decline with time and the inverted P Cyg polarization profiles of lines (Jeffery, 2004). The position angle is constant as a rule during a long period of time.

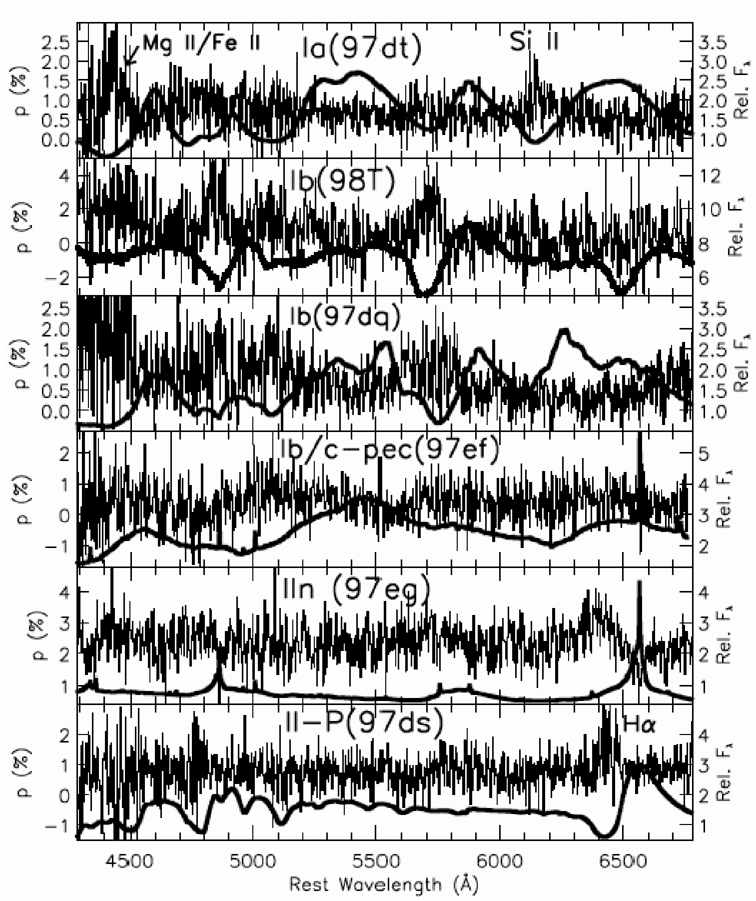

Figure 1: Polarization data for six SNe of various types from Leonard et al., 2000.

A different problem in the interpretation of all SN polarization measurements is proper removal of interstellar polarization which contaminates intrinsic polarization. Though the interstellar polarization (ISP) is slowly varying and quite well follows the empirical Serkowski law, sometimes ISP can completely distort an intrinsic polarization spectrum. The correction for ISP is really based on the observed SN data themselves and needs a detailed and careful consideration.

2 Results of Some Observations

Polarization data for six SNe of various types are shown in Fig.1. These data are taken from Leonard et al. (2000) (see also Filippenko and Leonard, 2003). As a rule, the spectropolarimetric data show that normal SN Ia are not highly polarized. Their intrinsic polarization is detected at levels around $(0.1 \div 0.3)\%$. The higher polarization of core-collapse SNe changes with time and the polarization after optical maximum is larger than before. All these objects studied possess also spectropolarimetric line features. Quite an interesting fact is that the strongest spectropolarimetric features are often seen in the troughs of strong P-Cyg lines. A simple explanation of this fact may be that P-Cyg absorption selectively blocks photons coming from the central, more forward-scattering and thus less polarized regions. This phenomenon is enhancing the relative contribution of the more highly polarized photons from the limb regions.

In Fig.2 the results of polarimetric and photometric observations of SN 2005cs are presented. Polarimetric observations in the R band were carried out during 20 nights from July 6 till August 22

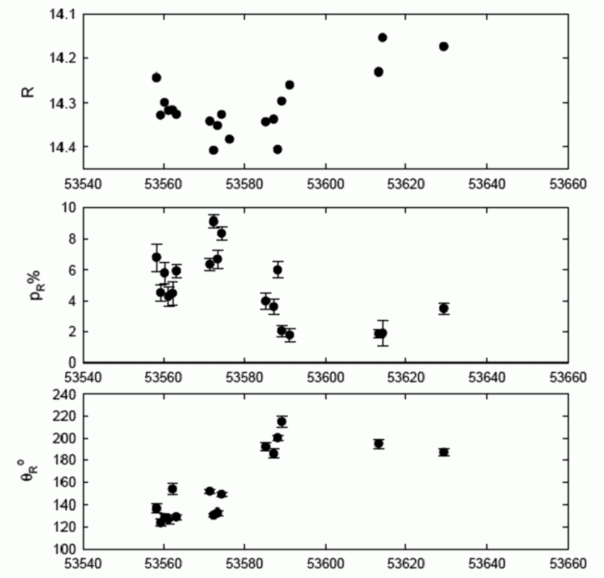

Figure 2: Results of polarimetric and photometric observations of SN 2005cs.

2005 with the 70-cm telescope AZT-8 of CrAO (see Gnedin et al., 2007). The maximal magnitude of intrinsic polarization of SN 2005cs is to be $\sim 8\%$. But the most peculiar event was the detection of a jump of positional angle at 90 degrees about 30 days after the explosion. We interpreted this event as a result of producing a bipolar jet and its interaction with circumstellar matter of a strong wind of the presupernova (see in detail below). The origin of such a bipolar jet is an explosion of a magnetized massive star.

3 Physical Mechanisms of Generation of Polarized Radiation of Supernovae

There is another mechanism of generation of polarized radiation developed by Gnedin and Silant'ev (1984, 1997). Emission of a star with a dipole magnetic field surrounded by a spherically symmetric plasma envelope will acquire an integral linear polarization as a result of scattering on electrons. The polarization is produced due to the effect of Faraday rotation of a polarization plane on the path length of photon between successive scatterings (Dolginov et al., 1995). The reason of producing polarization is the dependence of the Faraday rotation angle on the angle between the directions of magnetic force line and line of sight, as a result of the compensation of various electric vector directions from separate regions of a spherically symmetric radiation source (Fig.3).

The more popular interpretation is that the conical jet is the basic element of an explosion of a supernova and a phenomenon of cosmic gamma-ray bursts (GRB) (Fig.4). The difference between these phenomena is based on the various polarization mechanisms: electron scattering for supernovae and synchrotron emission for GRBs. A commonly accepted point of view is that the SN jet is to be of non-relativistic origin and GRB jet is to be relativistic. The central problem now is the connection between SNe and GRBs, therefore strong evidence exists for the direct link between the SN explosion of a massive star and long duration GRBs.

Fig.5 presents our calculations (Gnedin et al., 2006) of polarization and positional angle of the total radiation from magnetized optically thin conical jet versus depolarization parameter δ multiplied by optical thickness magnitude. The depolarization parameter δ is determined by the

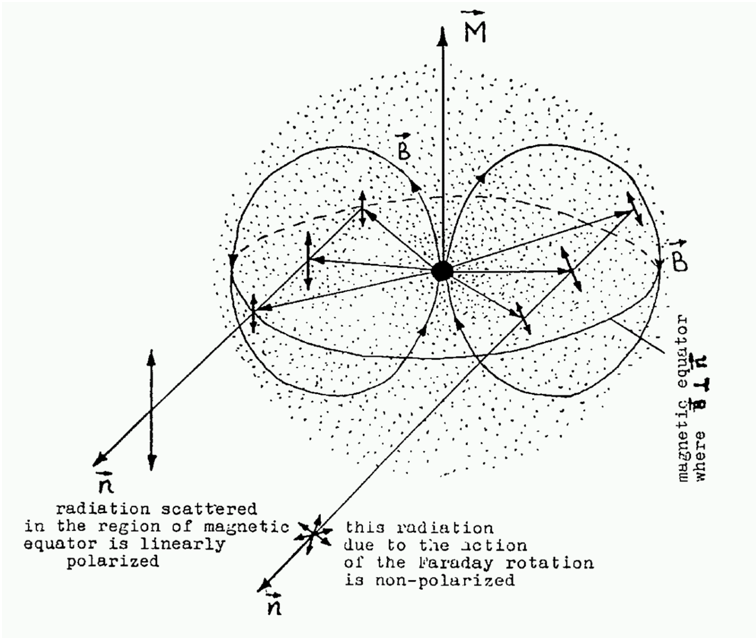

Figure 3: Star with a dipole magnetic field surrounded by a plasma envelope.

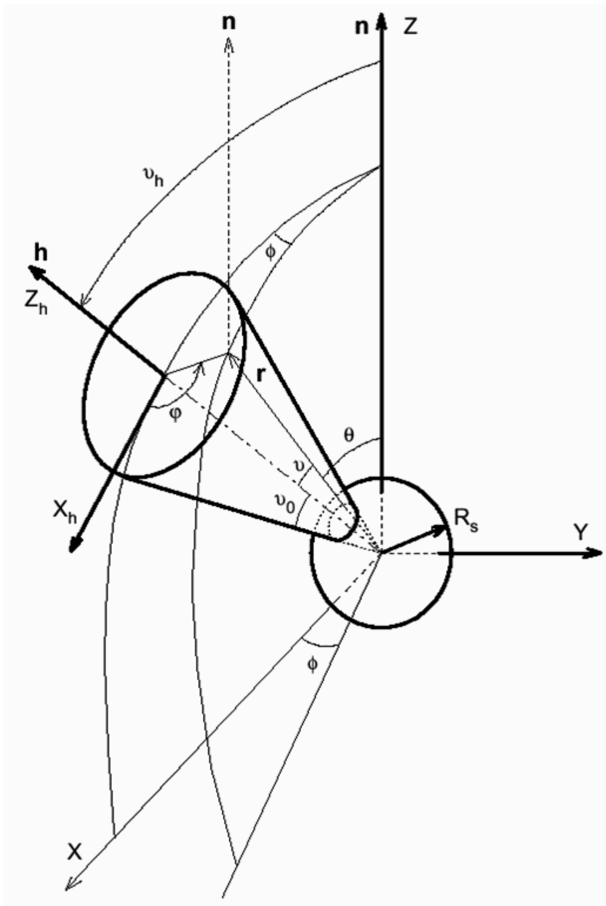

Figure 4: The conical jet.

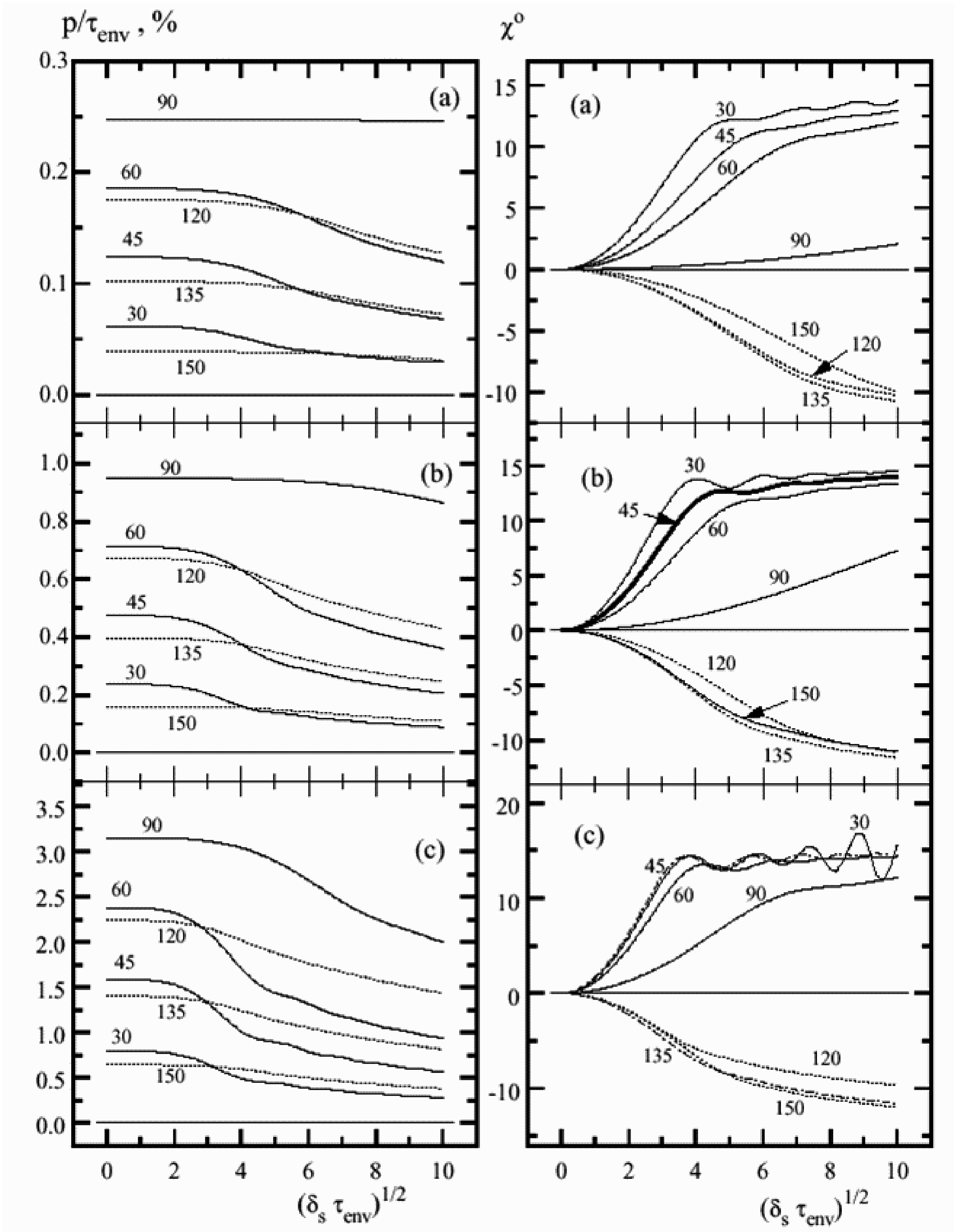

Figure 5: Polarization and positional angle of the total radiation from magnetized optically thin conical jet with radial magnetic field.

product of magnetic field strength B and the square of the wavelength λ (Gnedin and Silant'ev, 1997):

$$\delta = 0.8(B/1G)(\lambda/1mM)^2 . \quad (1)$$

Magnetic field in Fig.5 is radial.

Fig.6 shows the same pattern only for a bipolar magnetic jet. A bipolar jet model for supernova polarization was proposed by Jeffery (2004) and developed by Chugai (2006). The light from the main component of the supernova scatter off electrons in the jets and is polarized: this polarized light is added to the direct emission from the main component and causes the overall SN emission to be polarized. Our calculations show that, at first, the polarimetric observations of core-collapse SNe confirm that they are really jet-dominated phenomena. Secondary, using the results of calculations by Gnedin et al., 2006, we estimated the constrains on the magnetic field strength in the region of SN emission. The method of Gnedin et al. (2006) allows determination of the exact magnetic field strength if the measurements of linear polarization are made at least in two colour bands. Fig.3 from Gnedin et al. (2006) shows that if the wavelength dependence of the polarization net is absent (it means the absence of Faraday depolarization effect), one can get the following estimation of the magnetic field strength in region of polarized radiation generation:

$$B < 4/0.8\tau(\lambda/1mM)^2 = 10/\tau Gs. \quad (2)$$

The maximal value of observed polarization corresponds to the case where $\tau \sim 1$ and the angle between the directions of the jet axis and the line of sight is to be $\sim 90^0$.

We use the estimation of typical size of SN 2005cs polarized radiation region (Gnedin et al., 2007): $R \approx 3.4 \times 10^{15}$ cm. If one suggests the conservation of magnetic flux, it is possible to estimate the maximal magnitude of the magnetic field of protoneutron star:

$$B_{SN} = 10(R/R_{pns})^2 \approx 3 \times 10^{15} G, \quad (3)$$

where $R_{pns} = 2 \times 10^8$cm is the commonly accepted value of the radius of a protoneutron star that is believed to be a supernova remnant after an explosion. Curiously, but this magnitude ($\sim 10^{15}$G) is typically expected for magnetars. The most effective mechanism of generation of such an extremely strong magnetic field is magneto-rotation instability (Bisnovaty-Kogan, 1971).

4 Serkowski Law and Intrinsic Polarization of Stars with Magnetic Field

Recent studies (Leonard et al., 2002) have found the Type II plateau SN 1999gi in NGC 3184 to be highly polarized, the maximal degree of polarization measured in the optical bandpass being equal to $P_{max} = 5.8\%$.

From the convincing fit of the "Serkowski" interstellar polarization (ISP) curve to the observed continuum polarization shape of SN 1999gi Leonard et al. (2002) concluded that the bulk of the observed polarization is likely to be of interstellar origin in NGC 3184, but is not intrinsic in SN 1999gi. But empirical relation between interstellar absorption, the reddening $E(B-V)$ and interstellar polarization $P_l \sim 3E(B-V)\%$ (mean value) or $P_l \approx 9E(B-V)\%$ (maximal value) contradicts to ISP origin because the reddening observed for the host galaxy (NGC 3184) is extremely small: $E(B-V) = 0.21 \pm 0.09$. It means that the maximal value of ISP can not exceed 1.9%, that contradicts to observed data. Therefore Leonard et al. (2002) proposed that the dust has the highest polarization efficiency for a single sight line in either the Milky Way or an external galaxy.

We propose another interpretation of results of spectropolarimetric observations of SN 1999gi. Our basic idea is that polarization must be of intrinsic origin. Our new interpretation allows us to

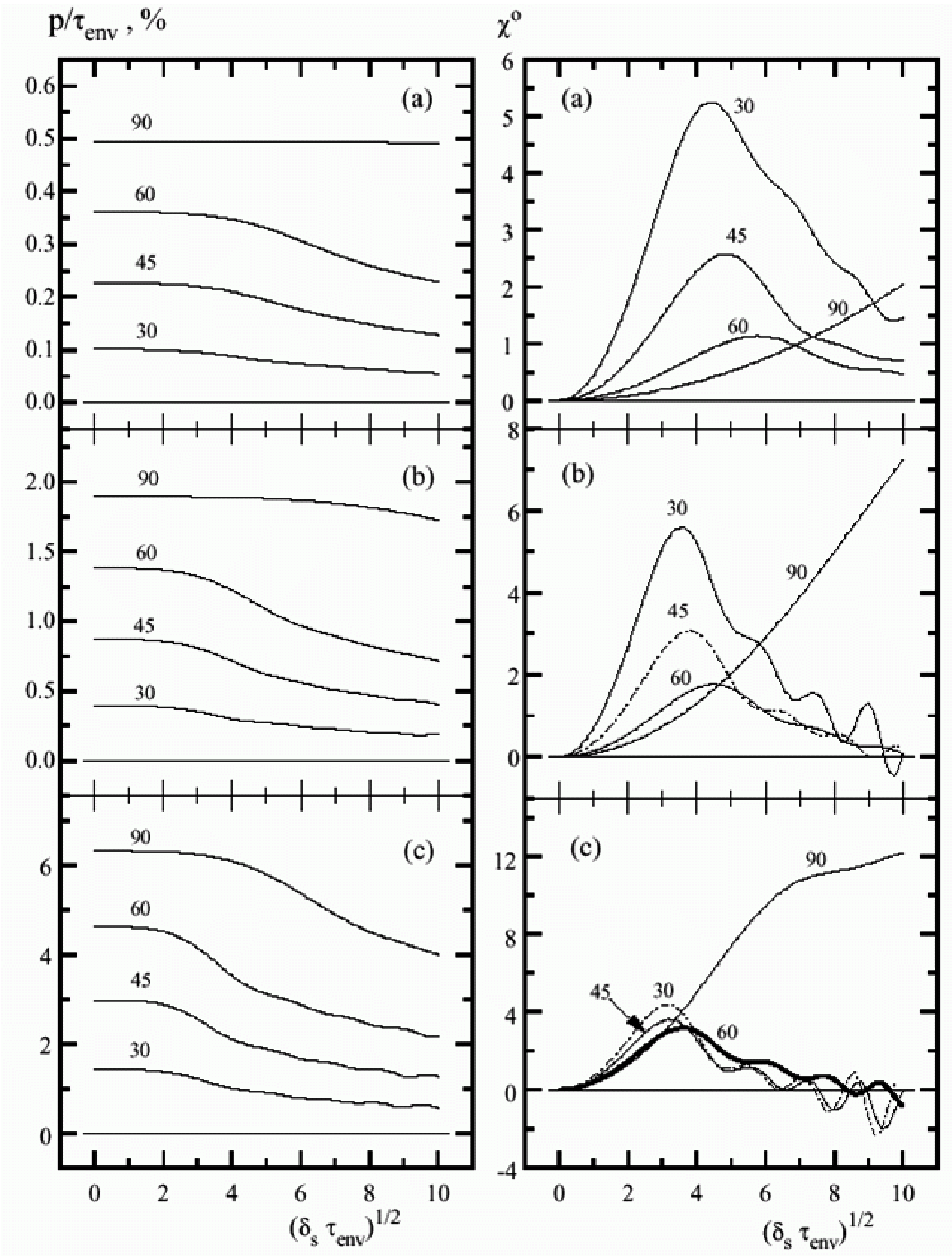

Figure 6: Same as Fig.5 but for bipolar magnetic field.

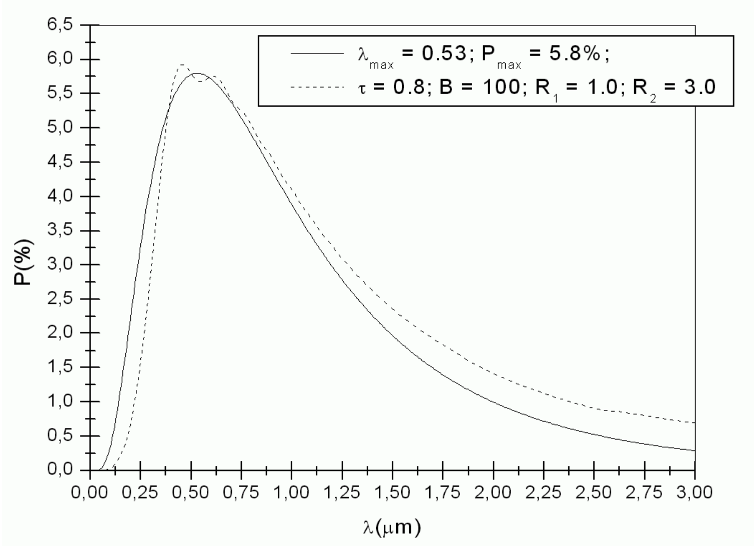

Figure 7: Comparison of "Serkowski" curve with parameters $\lambda_{max} = 0.53mM$ and $P_{max} = 5.8\%$ and results of calculations of Piotrovich (2006).

keep traditional model of SN but with essential addition — including magnetic field in supernova phenomenon. It appears that polarization of radiation can be produced as a result of electron scattering in spherically symmetric envelope if a star has a magnetic field (see, for example, Gnedin et al., 2005). The calculations of Piotrovich (2006) have shown that if the distribution of electrons in such an envelope is homogeneous, the wavelength calculated polarization is to be close to the "Serkowski" curve.

Fig.7 presents the comparison of the "Serkowski" curve with parameters $\lambda_{max} = 0.53mM$ and $P_{max} = 5.8\%$, which corresponds to observed data of SN 1999gi, and results of calculations of Piotrovich (2006). It is suggested that the bulk of SN has a magnetic field strength of $B = 100\,\mathrm{G}$ and the circumstellar spherically symmetric envelope with the hole in its center has the homogeneous electron density with the inner radius $R_0 = R_b$ and the outer radius $R_1 = 3R_b$, the optical thickness of the envelope $\tau_T = 0.8$. The agreement of these data is quite good. The comparison of observed wavelength dependence of SN 1999gi polarization with the calculated by Piotrovich (2006) dependence is presented in Fig. 8. Here it is pictured the "Serkowski" curve with the parameters presented in Fig.7. One can conclude that the SN polarization produced by electron scattering in the homogeneous density envelope with a magnetic field and a hole near the SN photosphere can mimic the Serkowski law for the polarization wavelength dependence.

We would like to comment that the new fact of discovery of, so-called, SuperSerkowski behavior of ISP may be explained in the same manner.

5 Conclusions

1. The intrinsic polarization of supernovae confirms strong asphericity of SN envelopes and existence of strong jets in exploding matter.

2. The existence of jets reveals strong resemblance between phenomena of supernova and cosmic gamma-ray burst.

3. We found the record net polarization for SN 2005cs and the interesting phenomenon of a jump

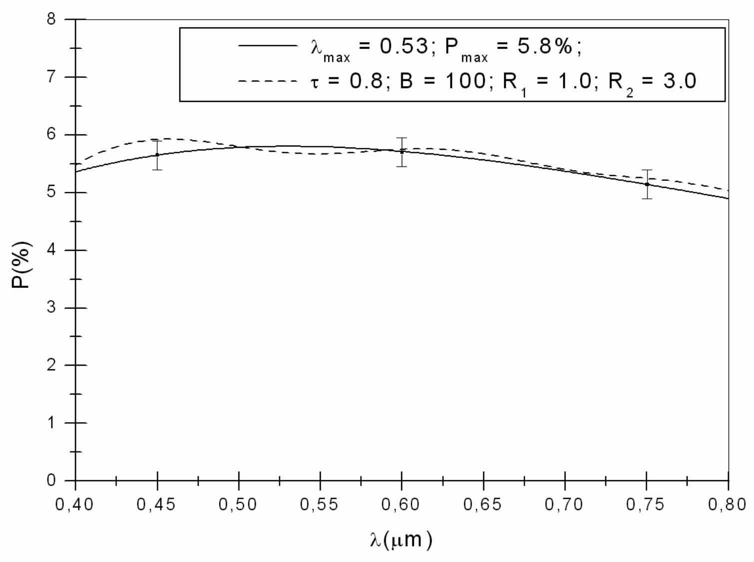

Figure 8: Comparison of observed wavelength dependence of SN 1999gi polarization with that calculated by Piotrovich (2006).

of positional angle during the supernova light curve evolution.

4. We discovered the phenomenon when the intrinsic polarization of a supernova produced by electron scattering in the homogeneous density envelope with magnetic field and with a hole near the supernova compact remnants can mimic the Serkowski law for the polarization wavelength dependence.

5. The same phenomenon can explain SuperSerkowski behavior of interstellar polarization for some galactic directions.

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