# Study of Envelope Velocity Evolution of Type Ib-c Core-Collapse Supernovae from Observations of XRF 080109 / SN 2008D and GRB 060218 / SN 2006aj with BTA

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Results of modeling the spectra of two supernovae SN 2008D and SN 2006aj related to the X-ray flash XRF 080109 and gamma-ray burst GRB / XRF 060218, respectively, are studied. The spectra were obtained with the 6-meter BTA telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences in 6.48 and 27.61 days after the explosion of SN 2008D, and in 2.55 and 3.55 days after the explosion of SN 2006aj. The spectra were interpreted in the Sobolev approximation with the SYNOW code. An assumption about the presence of envelopes around the progenitor stars is confirmed by an agreement between the velocities of lines interpreted as hydrogen and helium, and the empiric power-law velocity drop with time for the envelopes of classic core-collapse supernovae. Detection of a P Cyg profile of the H $\beta$  line in the spectra of optical afterglows of GRBs can be a determinative argument in favor of this hypothesis.

#### 1. INTRODUCTION

The modern classification of core-collapse supernovae includes several subtypes. If the spectra demonstrate hydrogen lines, then the supernova belongs to the II type. Its light curve shape is determined by the hydrogen recombination features in the envelopes. If a star loses its hydrogen envelope, but the helium shell is still present in the spectrum, then the star is classified into the Ib type. The impacts of hydrogen recombination are absent in its light curve, and its shape is determined by the heating of the emitting matter as a result of the  $^{56}{\rm Ni} \rightarrow ^{56}{\rm Co} \rightarrow ^{56}{\rm Fe}$  decay, depending on the

explosion energy. If the helium envelope is lost and the spectra show only the traces of heavier elements (O, Mg, Si, S, Ca, Fe), then the supernova is classified into the Ic type. Different subtypes of supernovae vary by different explosion energies, and, consequently, by the velocities of matter expansion in the envelopes.

Since in some cases the classification depends on the phase of the supernova at the moment of observation, some intermediate types are introduced: Ib/c (appearance of weak helium lines in late spectra), IIb (disappearance of hydrogen lines in late spectra). The classification of corecollapse supernovae can be conceived as a manifold of intermediate subtypes, depending continuously on the initial parameters of the progenitor of a shock wave through the wind envelope surstar. rounding a massive SN progenitor star, which

This paper discusses the manifestations of stellar-wind envelopes around the progenitor stars of an X-ray flash XRF 080109 and a gamma-ray burst with a strong X-ray component GRB / XRF 060218. Some signs of supernovae (SNe) were noticed in the spectra and light curves of both events, which allowed studying these phenomena from the very start of the explosion (unlike most SNe that are detected at the moments close to the "classical" maximum of the light curve). The study of this kind of phenomena makes it possible to approach the solution to the supernova explosion mechanism and the origin of gamma-ray bursts.

On January 9.57, 2009 (UT) the X-ray telescope XRT on board of the Swift space observatory registered an X-ray flash XRF 080109. The X-ray component was detectable for about 15 minutes [1, 2]. The Burst Alert Telescope (BAT) did not detect any gamma-ray quanta. The passage of a shock wave through the envelope was observed in multi-color light curves during several days [2, 3]. The afterglow light curves and spectra distinctly showed signs of the supernova, designated as SN 2008D.

Almost two years earlier (on February 18.149, 2006) the same space platform *Swift* detected a peculiar gamma-ray burst with the SN signs in the afterglow spectra and light curves of GRB/XRF 060218/SN 2006aj. It is the first phenomenon for which we observed the passage

of a shock wave through the wind envelope surrounding a massive SN progenitor star, which manifested itself as a thermal component in the X-ray spectrum observed during the first 2 hours, and then as a powerful UV burst with the maximum observed in 11 hours after the burst [4, 5]. The effect of the shock wave passage is seen in the optical light curve as a relatively short peak several days of duration [5, 6].

In both cases the moment of the X-ray flash and/or gamma-ray burst registration was taken as the beginning of the SN explosion.

The structure of the paper is as follows: spectral observations and preliminary data processing are described in section 2; the interpretation of the obtained spectra with the SYNOW code is laid out in 3; a comparison of the obtained measurements of the photosphere and envelope expansion velocities with the analogous velocities of SNe that did not show any relation with gammaray bursts or X-ray flashes is in section 4; our conclusions are discussed in section 5.

### 2. SPECTRAL OBSERVATIONS

Optical afterglows of XRF 080109 and GRB / XRF 060218 were observed with the *SCORPIO* Optical Reducer mounted in the primary focus of the 6-m BTA telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). The VPHG550G grism covering the spectral range of 3500–7500 Å with a resolution (FWHM) of 10 Å was used as a dis-

persing element.

We obtained two spectra of SN 2008D: on January 16 and February 6, 2008 (6.48 and 27.61 days after the explosion). For SN 2006aj two spectra were obtained as well: on February 20 and 21, 2006 (2.55 and 3.55 days after the explosion). The data processing was standard and included: subtraction of the electronic zero (an additive component of the total signal produced by the CCD chip), flat-field correction (compensation of the CCD chip sensitivity irregularities), wavelength calibration with the aid of a comparison spectrum of a Ne-Ar lamp, atmosphere extinction correction, and calibration by the absolute flux with the use of observations of a spectrophotometric standard performed every night. Apart from that, the spectra of SN 2008D were subtracted for the contribution of the host galaxy, the spectral distribution of which is constructed from the regions located in immediate proximity to the supernova.

Then the observed spectra were corrected for the extinction in the Galaxy according to the dust distribution maps [7]. When taking the extinction into account, the dust-screen model was accepted, where the expression to account for extinction is of the form  $F_{int}(\lambda) = F_{obs}(\lambda)10^{0.4 \times k(\lambda)E(B-V)}$ , where  $F_{int}(\lambda)$  and  $F_{obs}(\lambda)$  are the emitted (without absorption) and observed fluxes, respectively. The Milky Way extinction curve  $k(\lambda)$  was taken from the paper [8]. The spectra of SN 2008D were as well corrected for the extinction in the host

galaxy according to the data from [3]. The absorption in the host galaxy of SN 2006aj is negligible [9].

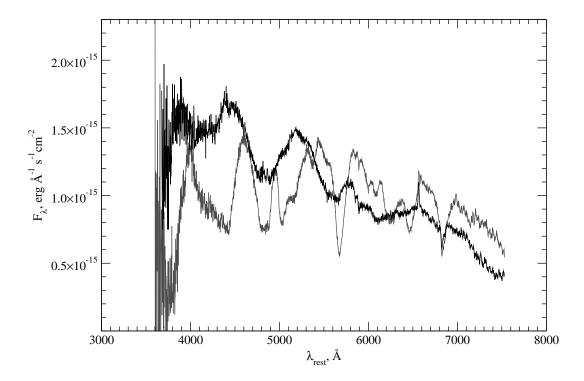
Before the interpretation, the spectra were transferred to the reference frames, associated with the gamma-ray burst or the X-ray flash (z=0.0331 for GRB/XRF 060218 and z=0.007 for XRF 080109, see Fig. 1). The redshifts were estimated from the shift of galactic emission lines, and are consistent with data published in the literature.

## 3. COMPARISON OF THE OBSERVED AND SYNTHETIC SPECTRA

To interpret the observed spectra in detail, we applied the multi-parametric SYNOW code [10], which was previously used for the analysis of spectra of core-collapse supernovae [11–13]. The code algorithm is based on the following assumptions: spherical symmetry; homologous expansion of layers  $(v \sim r)$ ; sharp border of the photosphere emitting a black-body spectrum and associated at early stages with a shock wave.

The code is used to identify the lines and find the expansion velocities of the layers in which they are formed. The P Cyg line profiles observed in the spectra of supernovae and modeled with the code are then divided into two types according to their shape:

• the lines formed in the layer undetached from the expanding photosphere;



**Figure 1.** Spectra of the supernova SN 2008D obtained with the BTA on January 16 (black line) and February 6 (grey line), 2008 in 6.48 and 27.62 days after the explosion, respectively.

• the lines appearing in the layer detached from the photosphere.

The version of undetached layers was used for the first spectrum of SN 2006aj. A combined version in which lighter ions are detached and the heavy ions are not detached from the photosphere was applied for the second spectrum of SN 2006aj and for both spectra of SN 2008D. The version choice was determined by fitting the parameters of every ion to the observed spectral features.

The model parameters of the input file and examples of interpretation of the SNe spectra are described in detail in the papers by code developers [10–13].

#### 3.1. Modeling of SN 2008D Spectra

The main absorption features are noticeable in both spectra (see Figs. 2 and 3) as P Cyg profiles of He I, Fe II, O I and, presumably, H I (a spectral feature near 6200 Å) lines. The main models containing H I as a candidate describing the above-mentioned feature are shown by the thick black line, and the observed spectra—by the thin grey noisy line.

spectrum described The first is best by the model with the following rameters: photosphere temperature  $T_{bb} = 8700 \text{ K},$ velocity of the photosphere  $V_{phot} = 17000 \text{ km/s}$ , maximum matter expansion velocity in the envelopes  $V_{max} = 70000 \text{ km/s}.$ The parameters of the best model for the

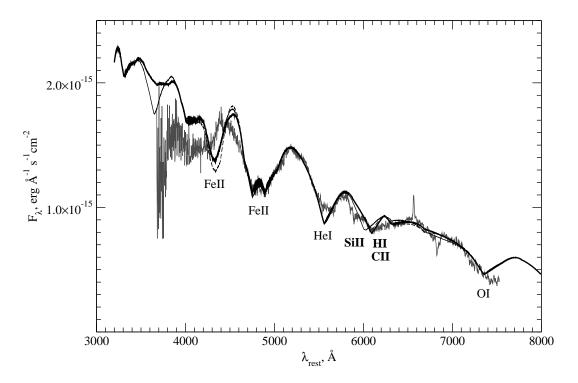


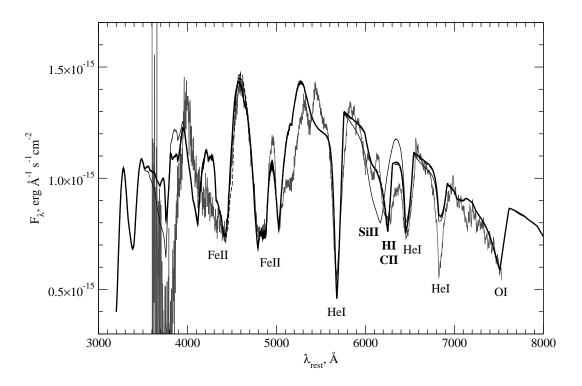
Figure 2. The spectrum of the supernova SN 2008D obtained with the BTA on January 16, 2008 in 6.48 days after the explosion (in the reference frame linked with the object, z = 0) is shown by the thin grey noisy line; the thick black line marks the model spectrum which contains HI; the model spectrum containing CII instead of hydrogen is marked by the thin dashed line; the model spectrum with Si II instead of hydrogen is marked by the solid thin black line.

second spectrum are as follows:  $T_{bb}=6000$  K,  $V_{phot}=8500$  km/s,  $V_{max}=70000$  km/s.

The temperature of the photosphere was determined by the slope of the observed spectrum. Since the shape of the spectra is very different from the Planck curve, the ions, describing the main spectral features were immediately included in the calculation. The photosphere velocity was adopted as equal to the velocity of the ionized iron lines [13]. The maximal velocity at the upper boundary of all envelopes  $V_{max}$  was estimated from the blue part of the P Cyg line profiles. Optical depth of the reference line [13] was selected in a way to best describe the ab-

sorption components of the P Cyg profile. The SYNOW code allows applying one of the two laws of the matter density decrease with distance: power  $(\tau(r) \propto v(r)^{-n}$ , where  $v \sim r$ ), and exponential  $(\tau(r) \propto \exp(-v(r)/V_e)$ , where  $V_e$  is the characteristic velocity of the layer, which determines the size of the envelope and the width of the absorptions in the observed spectrum). We used the exponential law in our calculations. The parameters of the main models that take hydrogen into account are presented in Table 1.

As an alternative interpretation of the spectral feature near 6200 Å, we considered the model calculations of synthetic spectra contain-



**Figure 3.** The spectrum of the supernova SN 2008D obtained with the BTA on February 6, 2008 in 27.62 days after the explosion. The markings are the same as in Fig. 2.

Table 1. Parameters of the models which best describe both spectra of SN 2008D. The parameters correspond to the models, marked with thick black lines in Figs. 2 and 3;  $\tau$  is the optical depth of the reference line of every ion;  $V_{min}$  is the minimal layer velocity of every ion;  $V_e$  is the characteristic velocity in the applied relation between the optical depth and the expansion velocity  $\tau(r) \sim \exp(-v(r)/V_e)$ , where  $v \sim r$ ;  $V_{phot}$  is the photosphere velocity;  $V_{max}$  is the velocity at the upper boundary of all envelopes;  $T_{bb}$  is the black body temperature of the photosphere, forming a continuous spectrum.

Parameters	First spectrum (6.48 days)				Second spectrum (27.62 days)				
Ions	ΗΙ	HeI	FeII	OI	ΗΙ	HeI	FeII	OI	
au	0.4	0.5	1.0	0.5	0.5	3.0	2.0	0.3	
$V_{min},{ m km/s}$	23000	17000	17000	17000	15000	10500	8500	10500	
$V_e,\mathrm{km/s}$	8000	4000	3000	4000	3000	1000	3000	4000	
$V_{phot},\mathrm{km/s}$	17000				8500				
$V_{max},{ m km/s}$	70000				70000				
$T_{bb}$ , K	8700				6000				

ing the lines of Si II and C II instead of the H I supernovae spectra [13, 14]. In Figs. 2 and 3 the lines. These ions were frequently mentioned thin solid lines correspond to the models with in the literature on modeling the type Ib-c silicon taken instead of hydrogen:  $\tau = 0.005$ ,

the first spectrum (all the other parameters are identical to those in the model with km/s. hydrogen), and  $\tau = 0.5$ ,  $V_{min} = 8500 \text{ km/s}$ ,  $V_e = 5000 \text{ km/s}$  for the second spectrum. The models containing the Si II lines = 6347 Å) instead of HI lines are velocity-limited by the photosphere and can not describe the observed spectral features near 6200 Å according to the modern concepts on the radial stratification of elements [13].

The absorption feature near 6200 Å can as well be explained by the presence of ionized carbon CII with the following model  $\tau = 0.005$ ,  $V_{min} = 24000 \text{ km/s}$ ,  $V_e = 10000 \text{ km/s}$  for the first spectrum,  $V_{min}=16000~\mathrm{km/s},$  $\tau = 0.0008,$ and  $V_e = 3000 \text{ km/s} \text{ for the second spectrum}$ (the thin dashed lines in Figs. 2 and 3).

Thus, Si II can be excluded from the calculations of these two spectra of SN 2008D. CII line  $(\lambda_{rest} = 6580 \,\text{Å})$  remains a possible alternative for the description of the absorption feature near 6200 Å. The above mentioned feature can possibly be formed by a blend of the H $\alpha$  and C II lines. It is obvious that the final conclusion requires observations with a higher spectral resolution.

#### 3.2. Modeling of SN 2006Aj Spectra

The spectra of SN 2006aj obtained with the BTA in 2.55 and 3.55 days after the gammaray burst were modeled with the SYNOW code.

 $V_{min} = 17000 \text{ km/s}, \quad V_e = 10000 \text{ km/s} \quad \text{for The first observed spectrum is best modeled}$ with the photosphere expansion velocity of 33000 This parameter is within measurement errors of the photosphere expansion velocity, measured from the Swift/XRT/UVOT data  $((2.7\pm0.8)\times10^4 \text{ km/s } [4])$ . At the moment we started our spectral observations (roughly straight after the last observation of the UV flash with the Swift/UVOT), the photosphere velocity remained within approximately Moreover, the early specthe same limits. trum shows a broad continuum depression at 5900–6300 Å and an almost imperceptible excess at 6300–6900 Å, which is best described by the H $\alpha$  P Cyg profile with the same velocity of 33000 km/s. For the fitting we used different models of the case where the layers are undetached from the photosphere, but the velocities of the photosphere and ions remained equal to 33000 km/s. The model parameters, the fitting of the observed spectrum, and detailed comments are given in [6].

> The velocities best describing the second spectrum (3.55 days after the burst) are within the limits 18000 km/s  $\leq$  { $V_{phot}$ ,  $V_{min}$ }  $\leq$  24000 km/s. The parameters of the model spectrum describing the observed spectrum, and the selected values of model parameters are laid out in [6].

> Using the best models of the SN 2006aj and SN 2008D spectra, we measured the hydrogen and helium envelope velocities, and the velocities of photosphere expansion for the respective observation epochs (see Table 2). The earliest

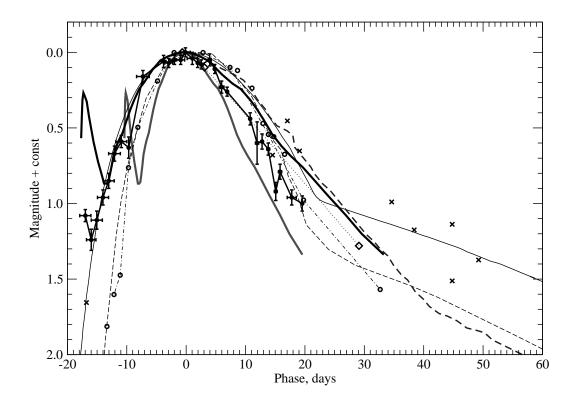


Figure 4. Comparison of light curves of the following supernovae in the V-band: SN 1983N [15–17]; SN 1984L [17]; SN 1999dn [18]; SN 2000H [19]; SN 2008D [3]; SN 2006aj [6]. The thick grey line shows the light curve of SN 2006aj without scaling along the time axis; the thick black line shows the same light curve scaled along the time axis with a factor of 1.7. The SN 2008D light curve is shown with the black line connecting the points with bars.

spectra of SN 2006aj demonstrate one the highest observed expansion velocities of the order of 0.1 of the speed of light. The teams of Kunugasa and Sahu ([21, 22]) describe similar expansion velocities observed in the early spectra of type Ic supernovae SN 2002ap and SN 2007ru, which indicates the presence of not just a unique object but rather a class of events capable of showing such high velocities.

We compared the velocities obtained for SN 2008D and SN 20006aj with an empiric law of photosphere and envelope velocity decrease for 11 type Ib supernovae from [11] using the scaling factor for SN 2006aj that was obtained based on a comparison of the light curves of the supernovae sample. This comparison is presented in Figs. 5 and 6.

## 4. PHOTOSPHERE AND ENVELOPE VELOCITIES

Light curves of different type Ib, Ic and Ibc supernovae mainly differ in absolute fluxes, widths of bell-shaped peaks near the main maxima, and their behavior at late phases of the flash. However, the light curve shapes of dif-

Table 2. Velocity variation of the hydrogen and helium envelopes and photosphere expansion of the supernovae SN 2006aj and SN 2008D after the explosion. The values in brackets indicate time after the maximum. The time of the maximum for SN 2006aj was determined as 10.4 days after the explosion (based on the V-band light curve) [9], and 19 days for SN 2008D [20].

	SN 2	006aj	SN 2008D		
	$2.55 \ (-7.85)$	3.55 (-6.85)	6.48(-12)	27.62 (+8)	
$V_{photosphere}$ , km/s	33000	18000	17000	8500	
$V_{hydrogen}$ , km/s	33000	24000	23000	15000	
$V_{helium}$ , km/s	33000	24000	17000	10500	

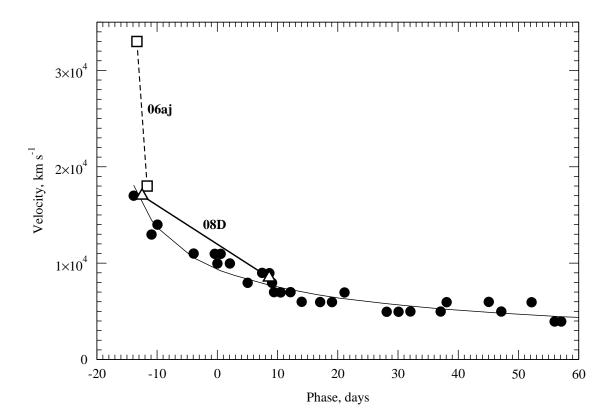


Figure 5. Variation of photosphere velocities, measured from the Fe II lines [11]. Photosphere velocities measured from our spectra are denoted as triangles for SN 2008D and squares for SN 2006aj. The scaling factor 1.7 was applied to the SN 2006aj photosphere velocity.

ferent supernovae near the maximum are similar SN 2008D and SN 2006aj in different bands with to each other. Valenti et al. [14] compared the the light curves of SNe from [11]. In the case light curves of SNe of different types via scal- of SN 2006aj, we applied the scaling factor 1.7 ing along the time axis. We applied an identi- (see Fig. 4). A comparison of light curves of the

cal method when comparing the light curves of SNe not observed in the V-band with the data

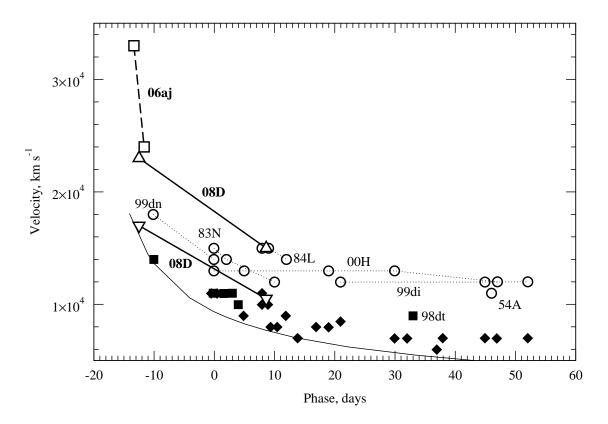


Figure 6. Minimal velocities from He I lines (filled squares for the case of layers undetached from the photosphere, filled diamonds for the detached lines), and H I lines (empty circles, always in detached layers) [11]. The curve represents the photosphere velocity drop power law from Fig. 5. Minimal velocities of He I lines for SN 2008D are indicated by triangles up, H I line velocities—by triangles down. The velocities of hydrogen and helium lines for SN 2006aj are indicated by squares. The scaling factor 1.7 was applied to SN 2006aj envelope velocities.

available in the B- and R-bands confirmed the accuracy of our choice of the scaling factor for the SN 2006aj light curve.

#### 5. CONCLUSIONS

An agreement between the velocities of photosphere expansion and those of the helium/hydrogen envelopes of the SNe associated with the X-ray flash XRF 080109 and the gamma-ray burst GBR 060218 argues for similar explosion dynamics of gamma-ray bursts and X-

ray flashes.

A comparison with analogous velocities of classical type Ib supernovae not accompanied by gamma- or X-ray bursts may indicate common properties of the progenitors of these two classes of phenomena, and similar explosion mechanisms.

Previously, an idea about the presence of hydrogen in the spectra of type Ib and Ic supernovae was suggested [13, 23]. The idea was confirmed in our paper [6] dedicated to the study of early spectra of SN 2006aj.

Branch et al. [23] list the main candidates for the description of a spectral feature near 6200 Å observed in the early spectra of supernovae. Apart from the hydrogen line H $\alpha$   $\lambda 6563$ these are: Si II  $\lambda 6355$  spaced from H $\alpha$  at 9500 km/s, Ne I  $\lambda 6402$  at 7360 km/s, and only C II  $\lambda 6580$  is spaced from the hydrogen line at 777 km/s, which can be within velocity measurement errors. Candidate velocities must agree with the photosphere velocity determined from the heaviest ions (e.g., from the ionized iron). Reasoning from the results of modeling the SN 2006aj and SN 2008D spectra, it can be concluded that the most possible sources of absorption near  $\lambda 6200$ are H $\alpha$   $\lambda 6563$  and C II  $\lambda 6580$ . To choose between these candidates we compared the velocity variability of hydrogen envelopes of the two SNe under study with the classical supernovae. The results of comparison of the velocity evolutions of different supernovae argue for the existence of hydrogen-containing envelopes around massive progenitor stars that appear before the explosion due to more or less powerful stellar winds.

Detection of P Cyg profile absorption components of other Balmer lines, in particular  $H\beta$   $\lambda 4861$ , can become a decisive argument in favor of hydrogen presence in the envelope. Since the optical depth of  $H\beta$  line is smaller than that of  $H\alpha$ , there arises a problem of its detection in a noisy spectrum among numerous lines of heavy metals, particularly, Fe II. Detailed long-term observations of the evolution of subtle details in the spectra obtained with a high signal/noise ratio can solve this problem.

#### **ACKNOWLEDGMENTS**

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