Core-Collapse Supernovae Overview with Swift Collaboration

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Core-Collapse Supernovae Overview with Swift Collaboration

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The Core-Collapse supernovae (CCSNe) mark the dynamic and explosive end of the lives of massive stars. The mysterious mechanism, primarily focused with the shock revival phase, behind CCSNe explosions could be explained by detecting the corresponding gravitational wave (GW) emissions by the laser interferometer gravitational wave observatory, LIGO. GWs are extremely hard to detect because they are weak signals in a floor of instrument noise. Optical observations of CCSNe are already used in coincidence with LIGO data, as a hint of the times where to search for the emission of GWs. More of these hints would be very helpful. For the first time in history a Harvard group has observed X-ray transients in coincidence with optical CCSNe. This discovery has proven that even if a supernova had its light absorbed with dust, X-ray transients that are more penetrating, and thus could be used as a hint on where to search for GWs. The SWIFT satellite can monitor galaxies with an X-ray probe. The main goal of this project will be to quantify the benefits for LIGO by using the SWIFT satellite to monitor galaxies within 20 Mega parsecs from Earth.

I. INTRODUCTION

The Core-Collapse supernovae mark the dynamic and explosive end of the lives of massive stars by releasing as gigantic bursts of energy, and thus are one of the most fascinating phenomena in the Universe. As time carries on, these explosions give birth to neutron stars and black holes, which in turn fuel galaxy evolution through the injection of heavy elements and mechanical energy. Ideally, a supernova explosion involves the collapse to a proto-neutron star of the evolved core of a massive star that exceed the set Chandrasekhar mass. A shock wave is launched from the proto-neutron star and plows through the stellar mantle. When the shock breaks out of the star’s surface, it lights up the star in a supernova explosion.

A core collapse supernova usually stems from a massive progenitor star that develops an iron core. This approximate 4/3 polytrope then becomes unstable and collapses, which takes around 100 ms. During the collapse, neutrinos are trapped and thus the core contracts adiabatically. And, at the super nuclear density, a hot proto-neutron star forms. And, during the bounce period, gravitational waves are emitted.

In the coming years, the gravitational wave detectors, LIGO and Virgo, currently in the process of technological upgrading, will reach sufficient sensitivity to observe for the first time gravitational waves, opening a new observational window to the Cosmos. One promising source of gravitational waves detectable by the ground-based interferometers is the core-collapse of massive stars, which give rise to supernovae. Core-collapse supernovae are one of the most energetic events in the Universe. They emit photons, neutrinos and gravitational waves and are ideal laboratories for multi-messenger observations and studies. These supernovae are marked by a X-ray outburst, and therefore it is forecasted that the future wide-field X-ray surveys conducted using satellites, such as the Swift XRT, will document hundreds of SN each year during the exact time of explosion unlike the optical observations that associate a time delay with the observation of every SN captured.

II. SWIFT X-RAY TRANSIENT (XRT) SATELLITE OVERVIEW

NASA’s Swift satellite has completed ten years of amazing discoveries in time domain astronomy. Its pri-
ary mission is to chase gamma-ray bursts, otherwise known as GRBS, but due to its scheduling flexibility it has become a prime discovery machine for new types of behavior occurring. The list of major discoveries in GRBs and other transients includes the long-lived X-ray afterglows and flares from GRBs, the first accurate localization of GRBs, the discovery of GRBs at high redshift, supernova shock break-out from SN Ib, a jetted tidal disruption event, an ultra-long class of GRBs, high energy emission from flare stars, novae and supernovae with unusual characteristics, magnetars with glitches in their spin periods, and short GRB with evidence of an accompanying kilo nova. Swift has developed a dynamic synergism with ground based observatories. In a few years, gravitational wave observatories will come on-line and provide exciting new transient sources for Swift to study.

The logic used for selecting pointing for the Swift satellite was similar to that of ground-based telescopes, except that, because the narrower Swift FOV required greater precision, care was taken to ensure the target galaxies were within the selected field. The coordinates supplied to Swift for follow-up were those of the matched galaxy itself in cases where there was only a single galaxy in a pixel, but the center of the 0.4 by 0.4 pixel, which is defined as the smallest single component of a digital image, in cases where the central coordinates of an extended source were outside the pixel or there were multiple galaxies in the pixel. Since fewer follow-ups were allowed using Swift than with other scopes, a minimum requirement was placed on the statistic P contained within the pixels selected for X-ray observation.

More than seventy short GRBs have been found by Swift and other gamma-ray satellites. A sizable fraction have X-ray and optical afterglows; a few have been detected in the radio. X-ray flares suggest that the GRB central region is very likely still active after the prompt gamma-ray emission is over, but with a reduced activity at later times. In conclusion, Swift had discovered a considerable number of GRBs with their associated transients through their XRT X-ray light curves.

The XRT is a sensitive, flexible, autonomous X-ray CCD imaging spectrometer designed to measure the position, spectrum, and brightness of gamma-ray bursts (GRBs) and afterglows over a wide dynamic range covering more than 7 orders of magnitude in flux. The BeppoSAX satellite showed that accurate positions of gamma-ray bursts can be effectively determined using a high-resolution X-ray telescope, since all of the GRBs observed within 6-8 hours after the burst by the BeppoSAX X-ray telescopes have fading X-ray counterparts or afterglows, whereas only about 60% have optical afterglows. However, by the time that Beppo-SAX is able to observe a typical X-ray afterglow, its intensity has already dropped by 4-5 orders of magnitude. The Swift XRT will begin observations before the GRB ends in many cases, and will fill in the large time gap during which the Lorentz factor of the relativistic blast wave changes. XRT is sensitive in the energy band 0.2 to 10 keV, has an effective area of 110 cm² and has the capability to estimate an accurate position, accuracy better than 5 arcseconds, in less than 100 seconds. The XRT is a focusing X-ray telescope with a 110 cm² effective area, 23.6 x 23.6 arcminutes FOV, 18 arcseconds resolution (half-power diameter), and 0.2-10 keV energy range. The XRT uses a grazing incidence Wolter 1 telescope to focus X-rays onto a state-of-the-art CCD. The complete mirror module for the XRT consists of the X-ray mirrors, thermal baffle, a mirror collar, and an electron deflector.

### III. Technicalities of Swift XRT

The X-ray mirrors are the FM3 units built, qualified and calibrated as flight spares for the JET-X instrument on the Spectrum X-Gamma mission (Citterio et al. 1996; Wells et al. 1992; Wells et al. 1997). To prevent on-orbit degradation of the mirror module’s performance, it is be maintained at 20°C ± 5°C, with gradients of 1°C by an actively controlled thermal baffle (purple, in schematic below) similar to the one used for JET-X. A composite telescope tube holds the focal plane camera (red), containing a single CCD-22 detector. The CCD-22 detector, designed for the EPIC MOS instruments on the XMM-Newton mission, is a three-phase frame-transfer device, using high resistivity silicon and an open-electrode structure (Holland et al. 1996) to achieve a useful bandpass of 0.2-10 keV (Short, Keay, and Turner 1998). The FWHM energy resolution of the CCDs decreases from 190 eV at 10 keV to 50 eV at 0.1 keV, where below 0.5 keV the effects of charge trapping and loss to surface states become significant. A special electrode structure gives the CCD-22 excellent low energy quantum efficiency (QE) while high resistivity silicon provides a depletion depth of 30 to 35 microns to give good QE at high energies. The detectors operate at approximately -100°C to ensure low dark current and to reduce the CCD’s sensitivity to irradiation by protons (which can create electron traps that ultimately affect the detector’s spectroscopy).

The CCD consists of an image area of 600 x 602 pixels (40 x 40 microns) and a storage region of 600 x 602 pixels (39 x 12 microns). Each pixel corresponding to 2.36 arcseconds in the Swift focal plane. The readout register is split into two sections, and may be read out using either output node, or may be split and read out using both nodes simultaneously. The CCD may also be operated in timing mode or window mode, which allow faster readout of fewer pixels so that bright sources may be observed without saturation.

The mirror point spread function has a 15 arcsecond half-energy width, and, given sufficient photons, the centroid of a point source image can be determined to sub-arcsecond accuracy in detector coordinates. Based on BeppoSAX and RXTE observations, it is expected that a typical X-ray afterglow will have a flux of 0.5-5 Crabs in the 0.2-10 keV band immediately after the burst. This flux should allow the XRT to obtain source positions to
The energy resolution of the CCDs is shown in the figure above, in which the dotted line is the ideal (Fano-limited) resolution, the solid line is the predicted resolution for an EPIC MOS CCD and the points are measurements from a typical flight device. Below approximately 500 eV the effects of charge trapping and loss to surface states become significant.

better than 1 arcseconds in detector coordinates, which will increase to -5 arcseconds when projected back into the sky due to alignment uncertainty between the star tracker and the XRT.

The XRT resolution at launch was 140 eV at 6 keV, with spectra similar to that shown below. Fe emission lines, if detected, can provide a redshift measurement accurate to about 10%. The resolution will degrade during the mission, but will remain above 300 eV at the end of the mission life for a worst-case environment. Photometric accuracy is be good to 10% or better for source fluxes from the XRT’s sensitivity limit of $2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ to $8 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$ (about 2 times brighter than the brightest X-ray burst observed to date).

Calibration of the PSF and the effective area have been performed at Panter X-ray calibration facility. The calibration source was positioned at 130meters from the mirrors. Corrections for the divergence of the X-ray beam and for pile-up effects have been applied. In the figures below the results of the effective area calibration tests in Window Timing and Photo-Diode modes are shown. The data for the PSF calibration have been taken in imaging mode with more than 1000 counts in the image with a counter rate lower than 10000 counts/s. The PSF profile has fitted by a model composed by a Gaussian function for the central part of the profile and a King function for the PSF wings. An examples of PSF profile is shown in figure 4.

The mission requirements for the effective area, the PSF and the spatial resolution were met at the Panter Facility and through the detailed study of the PSF and the analytical model the PSF correction for astronomical sources can be calculated with great accuracy.

XRT image of GRB 050911 comparing the BAT error circle with the X-ray afterglow. The brightest source in the XRT field of view during the initial observation will almost always be the GRB counterpart, and so this source’s position can be sent to the ground-based observers for rapid followup with narrow FOV instruments, such as spectrographs.

The PSF is slightly blurred on axis and better at 7 arcminutes off-axis due to the fact that the CCD is intentionally offset along the optical axis from the best on-axis focus. An analytical model to describe the PSF as a function of energy and angle was constructed to calculate the PSF correction for a source with a generic spectrum in a generic position of the detector. This model always described the data with a precision better than 2%.

FIG. 2.

FIG. 3.

FIG. 4.
Table 1: XRT Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>Wolter I (3.5 m focal length)</td>
</tr>
<tr>
<td>Detector</td>
<td>E2V CCD-2</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>40 μm X 40 μm</td>
</tr>
<tr>
<td>Pixel Scale</td>
<td>2.36 arcsec per pixel</td>
</tr>
<tr>
<td>Field of View</td>
<td>23.6 X 23.6 arcmin</td>
</tr>
<tr>
<td>PSF</td>
<td>18 arcsec HPD at 1.5 keV</td>
</tr>
<tr>
<td></td>
<td>22 arcsec HPD at 8.1 keV</td>
</tr>
<tr>
<td>Position accuracy</td>
<td>3 arcsec</td>
</tr>
<tr>
<td>Energy Range</td>
<td>0.2-10 keV</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>140 eV at 5.9 keV (at launch)</td>
</tr>
<tr>
<td>Effective Area</td>
<td>135 cm² at 1.5 keV</td>
</tr>
<tr>
<td></td>
<td>20 cm² at 8.1 keV</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$2 \times 10^{-14}$ erg/cm²/s at 10⁴ sec</td>
</tr>
</tbody>
</table>

in Photon Counting mode

FIG. 5. Characteristics of the Swift XRT satellite.

IV. ESTIMATED RATE OF SNE WITHIN A CERTAIN DISTANCE FROM EARTH PER CENTURY

Luminosity is the total amount of energy emitted by a star, galaxy, or other astronomical object per unit time. It is related to the brightness, which is the luminosity of an object in a given spectral region. In SI units luminosity is measured in joules per second or watts.

The Eddington Luminosity is the maximum luminosity a body (i.e., a star) can achieve when there is a balance between force of radiation acting outward and gravitational force acting inward. This is primarily known as hydrostatic equilibrium.

$$\frac{du}{dt} = -\frac{\Delta p}{\rho} - \Delta \Phi = 0$$  \hspace{1cm} (1)

\(u\) is the velocity, \(p\) is the pressure, \(\rho\) is the density. \(\Delta \Phi\) is the gravitational potential. The equation demonstrates the mean acceleration, which is equal to zero. This makes sense due to the principle of hydrostatic equilibrium.

$$-\frac{\Delta p}{\rho} = \frac{\kappa}{c} F_{rad}$$  \hspace{1cm} (2)

This equation is applicable if the pressure is dominated by radiation pressure that is associated with a radiation flux, \(F_{rad}\). \(\kappa\) is the opacity of stellar material, and this may be substituted by \(\kappa = \frac{\sigma T}{m_p}\). \(\sigma T\) is the Thomson scattering cross section for electrons. \(m_p\) is the mass of the proton.

Then, the luminosity of a source bounded by a surface, \(S\), may be derived.

$$L = \int_S F_{rad} dS = \int_S \frac{c}{\kappa} \Delta \Phi dS$$  \hspace{1cm} (3)

Opacity is assumed, and therefore returns a constant that will be equated using Gauss’s Theorem and Poisson’s equation. This then will be substituted back into the luminosity equation as shown below.

$$L = \frac{c}{\kappa} \int_S \Delta \Phi dS = \frac{c}{\kappa} \int_V \Delta^2 \Phi dV$$  \hspace{1cm} (4)

$$4\pi Gc \int_V \rho dV = \frac{4\pi G M c}{\kappa}$$  \hspace{1cm} (5)

Then, applying this to a simplified version (such as pure ionized hydrogen), we achieve:

$$L = \frac{4\pi G m_p c}{\sigma T} \frac{M}{M_\odot} L_\odot$$  \hspace{1cm} (6)

The mass-luminosity relation is an equation giving the relationship between a star’s mass and its luminosity. The relationship is represented by the equation:

$$\frac{L}{L_\odot} = \frac{M}{M_\odot} a$$  \hspace{1cm} (7)

where \(L_\odot\) and \(M_\odot\) are the luminosity and the mass of the Sun and \(1 \leq a \leq 6\). The value \(a = 3.5\) is commonly used for main-sequence stars. This equation and the usual value of \(a = 3.5\) only applies to main-sequence stars with masses \(2M_\odot \leq M \leq 20M_\odot\) and does not apply to red giants or white dwarfs. As a star approaches the Eddington Luminosity then \(a = 1\).

For stars with masses less than \(0.43M_\odot\), convection is the sole energy transport process, so the relation changes significantly. For stars with masses \(M \geq 20M_\odot\) the relationship flattens out and \(L\) is linear to \(M\). It can be shown this change is due to an increase in radiation pressure in massive stars. These equations are determined empirically by determining the mass of stars in binary systems to which the distance is known via standard parallax measurements or other techniques. After enough stars are plotted, stars will form a line on a logarithmic plot and slope of the line gives the proper value of \(a\).

Now, the distance modulus equation is introduced. The relationship between the intensity ratios and magnitude differences must be derived and clarified firstly. There is a base understanding that magnitudes increase linearly, while intensity ratios increase logarithmically with a base of 2.5.

$$\frac{I_A}{I_B} = (2.512)^{m_B - m_A}$$  \hspace{1cm} (8)

Then, taking the log of both sides, the following equation is achieved.

$$\log_{10} \frac{I_A}{I_B} = \log_{10}(2.512)^{m_B - m_A}$$  \hspace{1cm} (9)
\[ \log_{10} \frac{I_A}{I_B} = (m_B - m_A) \log_{10}(2.512) \]  
(10)

\[ \log_{10} \frac{I_A}{I_B} = 0.4(m_B - m_A) \]  
(11)

\[ (m_B - m_A) = 2.5 \log_{10} \frac{I_A}{I_B} \]  
(12)

Now, taking this, there is a relationship clearly drawn between intensity and distance.

\[ \frac{I_A}{I_B} = \left( \frac{d_B}{d_A} \right)^2 \]  
(13)

\[ (m_B - m_A) = 2.5 \log_{10} \frac{d_B}{d_A} \]  
(14)

\[ (m_B - m_A) = 5 \log_{10} \frac{d_B}{d_A} \]  
(15)

where \( d_A \) is usually standardized to 10 pc. Now, to get to the blue luminosity equation, the derived distance modulus equation is taken,

\[ (m_B - m_A) = 5 \log_{10} \frac{d_B}{d_A} \]  
(16)

And, \( d_A \) is substituted by 10 pc.

\[ (m_B - m_A) = 5 \log_{10} \frac{d_B}{10 \text{pc}} \]  
(17)

\[ m - M = -5 + 5 \log_{10} d \]  
(18)

\[ \log_{10} d = 0.2(m - M + 5) \]  
(19)

\[ 10^{\log_{10} d} = 10^{0.2(m - M + 5)} \]  
(20)

\[ d = 10^{0.2(m - M + 5)} \]  
(21)

Now, taking this derivation, we set it equal to:

\[ \frac{L}{L_{\odot}} = \left( \frac{M}{M_{\odot}} \right)^a = m - M = 2.5 \log_{10} \left( \frac{d_B}{10 \text{pc}} \right)^2 \]  
(22)

And, the result is:

\[ \frac{L}{L_{\text{Milky Way}}} = \frac{d}{d_{\text{Milky Way}}}^2 \frac{b}{b_{\text{Milky Way}}} \]  
(23)

where \( L \) is the luminosity measured in W, \( d \) is the distance measured in m, and \( b \) is the brightness measured in W\,m\(^{-2}\). But, \( b \) can be replaced by \( I \), representing intensity. And, therefore the new equation turns out to be:

\[ \frac{L}{L_{\text{Milky Way}}} = \frac{d}{d_{\text{Milky Way}}}^2 \frac{I}{I_{\text{Milky Way}}} \]  
(24)

Now, correlating this with:

\[ d = 10^{0.2(m - M + 5)} \]  
(25)

The final blue luminosity to absolute magnitude relationship is derived, shown below.

\[ B = 10^{-20.8 - A/2.5} \]  
(26)

where \( B \) is the blue luminosity of each given galaxy, and \( A \) is the absolute magnitude of each given galaxy. 2.5 represents the actual intensity, which is the interval of brightness that corresponds to a magnitude interval of 1 that correlates to 10\(^{0.4}\), and is overall the ratio of brightness taken to 10\(^{4}\). -20.8 would correspond to the absolute magnitude of the Milky Way. This equation is basely derived from equation 3.

![Blue Luminosity of Galactic Distributions within a Given Distance](image)

FIG. 6. The correlation between the distance, measured in Mpc, up until 20 Mpc in contrast to the cumulative blue luminosity that was used as a substitution for galactic mass.

Since the correlation between mass of the galactic distributions and their given blue luminosity extracted from the Gravitational Wave Galaxy Catalog reference is very high, and the differences in the information derived relatively negligible, a safe assumption of blue luminosity...
being substitute for star formation region mass was assumed. The plot itself is a two dimensional curve of the galactic concentrations within a 20 Mpc field of view. This correctly maps out the major cluster distributions found within the galaxy, from the Milky Way galaxy, to the Andromeda Clusterings, to the Virgo SuperCluster and onwards within the given distance constraints.

Introducing basic constraints in relation to the potential number of SNe discovered using the Swift XRT technology, it was theorized that about a rough estimation of 1.02 SNe per milky way unit mass would be discovered. This would account for the y-axis presented in the graph, as the blue luminosity in correlation to the number of SNe found within each plotted galaxy would reach a cumulative total of about 270-300 SNe discovered within 20 Mpc using the optical visible range one. Comparison between our SNe rate and published measurements shows that they are consistent within each others uncertainties. These assumptions were based off of normalizing the blue luminosity of each individualized galaxy to the blue luminosity of the Milky Way, which was 2.3 $10^{10}$ solar blue luminosity. The reason for normalizing to the Milky Way was because, in general, spiral categorical galaxies produce a higher core-collapse supernova rate. Therefore, normalizing to the milky way galaxy assumes that we are specifically looking for higher supernovae rate producing spirals.

SN detection up to 20 Mpc because of the ninety percent dust obscuration dust elimination using the X-Ray transients. Otherwise impossible to see through optical observations due to dust obscuration. The cumulative numbers of SN seen around 270-300 at 20 Mpc all through theoretical basing. These would be the possible detections made through the use of SWIFT satellite (XRT base). But, there is a theorized larger portion of SNe that will be found in the x-ray region using the XRT portion of the Swift Satellite. It is important to note that currently only 20% of SNe may be observed using only the optical range.

The next steps were to focus on the morphological type of each of the individualized galaxies, as spirals were producing a higher rate of CCSN, while galaxies such as ellipticals (although possessing a higher blue luminosity) had an extremely low rate of CCSN production. Therefore, we had to identify the morphology of each respective galaxy and their position on the sky in respective right ascension and declination coordinates. But, not all the galaxies in the gravitational wave galaxy catalog possessed complete morphologies. Therefore, a plot showing the distribution of galaxies with and without morphological classification was drafted and is shown below.

Then, taking into account the summation of the total blue luminosity within 20 Mpc of the chosen galaxies, classified and unclassified, the fraction of blue luminosity taken by the classified and the fraction of the blue luminosity taken by the unclassified galaxies was derived. 98.91% of the blue luminosity within 20 Mpc was provided by the classified galaxies, and 1.10% of the blue luminosity within 20 Mpc was provided by the unclassified galaxies. From this, it was safe to assume a statistical correction that negates the unclassified galaxies in the drafting of the CCSN rate. The next step was to draft a plot that shows the number of galaxies within each respective square degree of the galactic plane in order to determine a final observation strategy in regards to which area of the sky will have the correct imposed CCSN rate. This plot is shown below.
FIG. 9.
The distribution of galaxies according to respective categorized morphology types in relation to their position in the sky in right ascension and declination coordinates.

FIG. 10.
The distribution of galaxies within 20 Mpc in correlation to their respective positions in the sky in right ascension and declination coordinates.

V. SODERBERG OVERVIEW

Overall, the general picture of the CCSNe has been recognized for many years. But, what we have failed to produce is the exact details of the explosion as most CCSNe simulations fail to produce an explosion. And, because of this, the gaps in our understanding was primarily due to the absence of detailed observations primarily in the first few day of the explosion as well as the relative overall difficulty in detecting the weak neutrino and gravitational wave signatures of a specific explosion. And, it is important to note that these signals often provide a direct view of the explosion mechanism of the CCSNe itself at the exact time of explosion.

In total, the resulting explosion ejects several solar masses, on average, of stellar material with a mean velocity of around 104 km/s, which amounts to a kinetic energy of about $10^{51}$ erg. For example, a solar mass less than of 56Ni that is synthesized during the time of the explosion has subsequent radioactive decay powers and, as well as the luminous optical light observed to peak about 1 to 3 weeks after the expected explosion. And, following this explosion, it has been theorized that prompt bursts of X-ray emissions will accompany the break-out of the SN shock-wave through the stellar surface, but the short durations that is about seconds to hours at the most and the lack of sensitive wide-filed X-ray searches have prevented their discovery until now.

Now, drawing on the optical, UV, Radio, and X-ray observations it was shown that the observed progenitor was compact, which referenced to be about $R_c = 1011$, and therefore was stripped of its outer Hydrogen envelope by a strong, steady stellar wind. These properties maintained consistent with those of the Wolf-Rayet (WR) stars, and overall favored the progenitors of Type Ibc SNe.

There was a specific observation at 2008 Jan 9 at 13:32:49 UT of the NGC 2770 galaxy, at a distance of 27 Mpc, where there was a discovery of an extremely bright X-ray transient during the scheduled Swift X-ray Telescope (XRT). Previous XRT observations of the same field about two days prior revealed no pre-existing source emission from this location. The transient was designated as an X-ray outburst (XRO) 080109 that lasted approximately 400 seconds. From these observations, the conclusion was reached that XRO 080109 was is indeed located in NGC 2770.

Simultaneous observations of the FOC with the Ultraviolet/Optical Telescope (UVOT) that was on-board Swift showed evidence just 1.4 hours after the outburst, which revealed a brightening UV/Optical counterpart that were confirmed by ground-based optical observations. Due to the prompt X-ray discovery, the transient was classified as a Type Ibc SN 2008D based on the lack of hydrogen and subsequent weak silicon features. And, the temporal coverage of our optical spectra exceeded those of most observed SNe, and came to par with the GRB-associated SNe (GRB-Sne) and SN 1987A.

From the observation of the provided spectra, there is a clear evolution from a mostly featureless continuum to broad absorption lines associated, which finally delved into strong absorption features with moderate widths. And, the spectra itself revealed the emergence of strong He I features within a few days of the outburst. And, was concluded that SN 2008D is a He-rich SN Ibc unlike GRB-SNe.

While UV/Optical observations probe the bulk material, radio and X-ray emission trace fast ejecta. The Swift follow-up observations of the XRO revealed fainter X-ray emission several hours after the explosion with $L_X \approx 2 \times 10^{40}$ erg/s (where $t \approx 0.2$ days). This emission exceeds the extrapolation of the outburst by many orders of magnitude, indicating that it is powered by a different mechanism. Using a high angular resolution observation from the Chandra X-ray Observatory (CXO) on Jan 19.86 UT we detect the SN with a luminosity, $L_X = (1.0 \pm 0.3) \times 10^{39}$ erg/s (which is about 0.3 - 10 keV), and further resolve three nearby sources
FIG. 11. The temporal evolution was characterized by a fast rise and exponential decay, which is often observed for a variety of X-ray flare phenomena. And thus, there was a determination that the onset of the X-ray emission to be \(t_0 \approx \text{Jan 9.564 UT} \). It is important to note that the X-ray and radio observations of SN 2008D are the earliest ever obtained for a normal SN Ibc. At \(t \approx 10\) days, the X-ray and peak radio luminosities are several orders of magnitude lower than those of GRB afterglows but comparable to those of normal SNe Ibc. This rate is at least an order of magnitude larger than for GRBs. On the other hand, with a core-collapse SN rate, the probability of detecting at least one XRO, if all such SNe produce an outburst, is about 50%.

But, it was noted that NGC 2770 hosted an unusually high rate of three SNe Ibc in the past 10 years. The elevated SN rate in NGC 2770, with a chance probability of \(\approx 10^{-4}\) may simply be a statistical fluctuation due to the given sample of \(\approx 4 \times 10^{3}\) known SN host galaxies. Or, a SN at the Time of Explosion may point to a recent episode of elevated star formation activity, perhaps triggered by an interaction with the companion galaxy NGC 2770B as there is only a separation of 22 kpc.

The XRO was in the FOV of the Swift Burst Alert Telescope (BAT; 15 - 150 keV) that began 30 minutes before and continued throughout the outburst. But, no \(\gamma\)-ray counterpart was detected through BAT. Therefore, the outburst observed was determined that it was not a GRB by integrating over the duration of the outburst, which was a factor that was three times higher than an extrapolation of the X-ray spectrum to the BAT energy band. The total energy of the outburst, \(E_x\), was about \(2 \times 10^{46}\), which was at least three orders of magnitude lower than typical GRBs. Overall, the properties of XRO 080109 are distinct from previously known and documented X-ray transients.

Since some SNe Ibc harbor GRB jets, we investigate the possibility that the XRO is produced by a relativistic outflow. In this scenario, the X-ray flux and simultaneous upper limits in the UV/Optical require the outflow to be ultra-relativistic with a bulk Lorentz factor, \(\gamma \approx 90\), but its radius to be only \(R \approx 10^{10}\) cm; \(\gamma = (1 - \beta^2)^{-\frac{1}{2}}\).

\[ \beta = \frac{v}{c}, \]  

(27)

where \(v\) is the outflow velocity and \(c\) is the speed of light. However, given the observed duration of the outburst, it is indicated that the relativistic outflow scenario is not self-consistent.

VI. SODERBERG SUPERNOVA RATE DERIVATION WITHIN 20 MPC

\[ \frac{\frac{4}{3} \pi (20 \text{Mpc})^3}{(1\text{Gpc})^3} \cdot \frac{6 \times 10^4}{1(\text{Gpc})^3(\text{yr})} \]  

(28)

\[ \frac{24\pi}{3} \cdot \frac{8(\text{Mpc})^3}{1(\text{Mpc})^3(\text{yr})} = \approx 200 \text{ SN per year} \]  

(29)

VII. CONSTRAINTS IMPOSED ON ESTIMATE OF SNE DISCOVERED WITHIN 20 MPC

The new estimates of local rates of SNe was derived by adding in the updated log of Evan’s search (reference to Evans et al 1989; Van den Bergh and Mc Clure), along with four other cumulative searches. The five total searches used were Asiago, Crimea, Calan/Tololo, and the OCA photographic surveys along with Evan’s visual...
search. The surveys were used to probe SN rates of different traces of star formation activity in galaxies. This was done by integrating colors, infrared luminosities, and nuclear activities. Thus, a relation between CCSNe and integrated galaxy color was found. This discovered relation was found consistent with prediction of galaxy evolutionary models. The relative SN rates with red shift can be used to probe average star formation rate history in galaxies. This would constrain scenarios for galaxy formation and evolution.

Another constraint to explore would be the rates of various SN types with different indicators of stellar population content of local galaxies in the local Universe. This was measured using a sample of galaxies which have been searched for SNe, the frequency and limiting magnitude of observations, instruments and techniques which are used for detection in order to assess search biases.

On a side note, it is important to note the factors that decrease SNe detection at the chosen distances. It is difficult to discover SN in the luminous inner regions of a galaxy than in its outskirts. The fraction of SNe lost is greater in more distant galaxies because of the small angular size of the galaxy image. To solve this, we will have to comprehend the radial distributions of SNe in galaxies at different distances. This would lead to an estimation up to fifty percent of SNe lost in photographic searches using the standardized Schmidt telescopes.

The natural interpretation of this bias is that SNe occurring in the disk of inclined spirals appear on the average dimmer than those in face-on spirals because of the increased optical depth through the dust layer. As a consequence, the probability of SN discovery in inclined spirals is reduced. In line with this interpretation, it is expected that the bias is more severe in searches carried out in the blue band, (e.g. photographic searches), than in visual ones (CCD searches in the red would be even less affected). As a first order approach to correct for the inclination bias, a plane parallel geometry for the distribution of dust in the disk of spirals was assumed. In this case, the average extinction of the SN population scales with sec i, where i is the inclination of the galaxy disk with respect to the line of sight. It was argued that this is evidence that dust is not uniformly distributed in the disk of spirals but is instead in discrete clouds. Until more evidence is available we have adopted, in analogy to C97, a conservative extinction law that is intermediate between the sec i and an empirical relation, derived from the assumption that the SN rate is the same in face-on and edge-on galaxies (see Section 3 for an alternative model). When such a correction is included, the computation the SN rates for the complete Evans search was carried out and compared with those obtained from the first ten years of the search and with those derived from the combined photographic search sample.

In the following, a brief description of the main characteristics of each SN search is given.

The SN search was conducted at Asiago from 1959 to 1990, initially with the 40 by 50 cm Schmidt telescope (S40) and, after 1967, also with the larger 92 cm Schmidt (S67). During the search, 31 SNe were discovered, and about 20 more were recorded in the survey plates (P1). The Crimea search started in 1961 using the 40 cm astrograph of the Sternberg Institute in Crimea. It announced the discovery of 21 SNe and 18 more were recorded. The Evan’s visual search was aimed at the prompt discovery of nearby SNe, and became the most successful visual SN search. At the beginning, in 1980, a 25 cm telescope was employed which was later substituted by a 41 cm telescope in November 1985. The SN sample counts 24 objects, with almost 100000 individual observations. The OCA search began in 1987 based on the 90 by 152 cm Schmidt telescope of the OCA. Differently from the others, the OCA search is not systematic (S40) and, after 1967, also with the larger 67 by 92 cm Schmidt (S67). During the search, 31 SNe were discovered, and about 20 more were recorded in the survey plates (P1). The Crimea search started in 1961 using the 40 cm astrograph of the Sternberg Institute in Crimea. It announced the discovery of 21 SNe and 18 more were recorded. The Evan’s visual search was aimed at the prompt discovery of nearby SNe, and became the most successful visual SN search. At the beginning, in 1980, a 25 cm telescope was employed which was later substituted by a 41 cm telescope in November 1985. The SN sample counts 24 objects, with almost 100000 individual observations. The OCA search began in 1987 based on the 90 by 152 cm Schmidt telescope of the OCA. Differently from the others, the OCA search is not systematic.

FIG. 12.

SN rates in spirals of different inclination (not corrected for the inclination bias).

<table>
<thead>
<tr>
<th>Evans search</th>
<th>photographic searches (from C97)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lat.</td>
<td>N. galaxies</td>
</tr>
<tr>
<td>[deg]</td>
<td></td>
</tr>
<tr>
<td>0-45</td>
<td>616</td>
</tr>
<tr>
<td>45-65</td>
<td>666</td>
</tr>
<tr>
<td>65-90</td>
<td>592</td>
</tr>
</tbody>
</table>

* 1SNu = 1SN (100yr)^{-1} (10^{56}Jy)^{-1}.

FIG. 13.

Comparison of the SN rate [SNu] obtained from the Evans updated statistics (1980-1998), the first 10 years of the search (1980-1989) and the combined photographic search sample.

FIG. 14.

The different rates calculated in the 1990’s with the most viable estimations made. We based off our renewed calculations off of Cappellaro 1997, which had a compilation of 5 refined searches.
by makes use of plates obtained for other purposes. In particular, there were not predefined sky fields and observing strategy. Most of the plates were very deep, with limiting magnitude up to 21-22 and therefore many faint SNe were found. On the 500 plates examined to the end of 1994, 68 SNe have been found. The Calan/Tololo search began in 1990. The scientific rationale was to produce a sample of SNe at moderate distances that would be suitable for cosmological studies. A 60 by 90 cm Schmidt telescope was employed for the regular monitoring of selected fields resulting in the discovery of 49 SNe.

The computational recipe involving these five searches was based on the present determination of the rate of SNe, which was based on the control time method that was introduced by Zwicky (1942).

The galaxy sample associated with each of the surveys, with the exception of the Evans’ search, was primarily based upon the wide field plates which in a single shoot allow the surveillance of many galaxies. Therefore, it is important to note that the galaxy sample is not defined by a priori but was selected according to the extraction from a suitable list that contained galaxies that would appear in at least one of the survey plates. For computational purposes, it is important to know each galaxy’s recession velocity, the morphological type, the luminosity and, for spirals, the axial ratio.

For each galaxy of the sample, of the 110 narrowed down to, the apparent light curve of a possible SN in that targeted galaxy needed to be computed. This calculation would depend on the SN type and on the galaxy distance. This would be given by the following equation.

\[ m_{sn}(t) = M_{0,sn} + \Delta m_{sn}(t) + \mu + A_g + < A_i > \]  

\( M_{0,sn} \) is the intrinsic absolute magnitude at maximum of the SN, \( \Delta m_{sn}(t) \) describes the light curve evolution relative to maximum, \( \mu \) is the galaxy distance modulus and \( A_g \) is the galactic absorption. Finally, \( < A_i > \) is the average extinction of the SN population in that galaxy due to the internal dust as seen from our particular line of sight.

In the present work, the calculation for the rates for the three basic types of SNe namely Ia, Ib/c and II is used. At present the statistics are not large enough to separate Ib from Ic that, or this reason, were lumped together. In PI the adopted templates for SN Ia and SN Ib/c were the same (although the absolute magnitudes at maximum were different). Instead in the present work, the adoption the light curves of SN 1990J (Della Valle et al., in preparation) was used as template for SN Ib/c. Concerning SN II, it is well known that they exhibit quite heterogeneous photometric behaviors with different light curve shapes and maximum luminosities (cf. Patat et al., 1993, 1994). To account for this, the calculation was done separately for the rates for the two photometric classes of IIP (plateau) and IIL (linear) and thus derived the total rate of SNII by summing the two contributions. It turns out that the results are very similar to those which are obtained by adopting, in the calculation of the control time, a light curve which is intermediate between Plateau and Linear. No account is made for the rare class of SN Ibn or for the possible existence of a separate class of faint SNII similar to SN 1987A.

In a first approximation, we can assume that ellipticals are dust free, that is \( < A_i > = 0 \) mag. Therefore by taking the average absolute magnitude of SN Ia in ellipticals (Ia are the only type of SNe found in these galaxies) we obtain directly \( M_{0,Ia} \). Dust extinction is certainly important in spiral galaxies. Direct estimates of the average absorption suffered by SN Ia in face-on spirals range from 0.4 mag (Miller and Branch 1990) to 0.7 mag (Della Valle and Panagia, 1992), that is the average observed magnitude of SN Ia is 0.4-0.7 fainter than the intrinsic value. On the other side there are indications that the intrinsic magnitude of SN Ia correlates with the Hubble type of the parent galaxies. Evidence are still preliminary but it seems that in spirals \( M_{0,Ia} \) is 0.3-0.5 mag brighter than in ellipticals.

Once the computations for each galaxy of the sample of the expected light curves, \( m_{sn}(t) \), of all SN types, the control time was derived which was the interval of time during which a possible SN in the \( j^{th} \) galaxy stays...
For the calculation of the control time, the light curves are truncated 400 days after maximum. The galaxy luminosity is introduced as a normalization factor because it has been demonstrated that the SN rate is proportional to the galaxy luminosity (Tammann 1974; PII).

For about 1/4 of the SNe of our sample no detailed classifications are available. Most of them are of type I but for a few (10 out of 110) not even this broad classification is available. The unclassified SNe have been redistributed among the three basic types according to the observed distribution in the merged sample, that is in E-S0 100% type Ia, in spirals 35% type Ia, 15% type Ib, 50% type II.

In C97 the SN Ia rate appeared to increase when progressing from early to late type galaxies whereas this effect had now nearly vanished. The relatively low rates of SN Ib/c compared with SNII were, instead, confirmed. The normalization of the SN rate to the galaxy blue luminosity has been introduced after the demonstration that the former scales with the latter. This is convenient because the integrated B magnitudes are available for a large number of galaxies and the B luminosity for a given galaxy type scales with the total mass at a first approximation. Physically, the blue luminosity is a good tracer of the young stellar population in starburst galaxies, but not in normal galaxies where a considerable fraction of the continuum luminosities is produced by old stars also in the blue. In principle, by using different photometric bands should be possible to sample selected stellar populations and hence to obtain useful information for progenitor scenarios. If all SN Ia result from low mass stars, the expected SN Ia rate per unit of H and K luminosities not to be correlated to galaxy type. The fact that the rate in these units increases considerably when moving from ellipticals to late spirals was taken to indicate that a significant fraction of SN Ia result from intermediate age stars. Even if their conclusion is probably correct, it must be stressed that these estimates were not direct measurements but a simple scaling of the SN rates in unit blue luminosity based on the assumption of an average B-H and B-K color per galaxy type. Because H and K photometry is available only for a small fraction of the galaxies in our sample, unfortunately, the SN rate in these units cannot be directly measured.

The average rate of SNe [SNu] for each SN search.

In the different panels we report for each search the distributions of r/R, the ratio of the distances from the nucleus of the SNe discovered to the semi-major axis of the parent galaxies. To improve the statistics for the Evans sample, the SNe discovered after 1989 were included.

The average rate of SNe [SNu] for each SN search.

Integrated broad band colors are very useful for statistical purposes, as they are reliable indicators of the galaxy stellar population with bluer galaxies expected to host stars that are younger and more massive than redder
ones. Colors are most interesting because, by using evolutionary synthesis models, it is possible to estimate the star formation rate per unit mass or luminosity required to produce a given integrated color for a given stellar population. It is well known that along the Hubble sequence the galaxy color becomes bluer moving from early to late types and that this corresponds to a sequence in star formation rate which is virtually zero in ellipticals and maximum in late spirals. However, especially in spirals, there is a significant dispersion in the average color from galaxy to galaxy, indicating that star formation rate can vary significantly even for a given Hubble type.

The rate of core collapse SNe (II+Ib/c) is higher in the bluer spirals. By using B-V color this effect is seen only for late spirals (the rate is higher by a factor of 1.7 for Sbc-Sd), but becomes clear for all spirals when using U-V color (over a factor of 2). Instead the rate of SN Ia is, within the uncertainties, independent on galaxy colors. And, dividing the galaxies into bluer and redder colors to a large extent corresponds to separating them into early and late type galaxies. Therefore, the great different in the CCSNe rates in bluer and redder galaxies simply reflects the facts that CCSNe are not found in early type galaxies.

The star formation rate itself is often taken in terms of per unit of blue luminosity. In general, for a galaxy of luminosity \( L_B \), because of the short life of progenitor evolution, the number of core collapse SNe per century corresponds to the number of new born stars within the appropriate mass range shown below:

\[
SN \text{ rate}[SNu] \times L_B \approx \frac{SFR \times f_{MU}}{< M_{SN} >} \times 100
\]

**FIG. 19.**

where \( f_{MU} \) is the mass fraction of stars which are born with mass in the range \( M_L \) to \( M_U \), the lower and upper limit for CCSNe progenitors, and \( < M_{SN} > \) is the average mass of SN progenitors.

Even if the exact coincidence of the two scales in our figure is to some degree fortuitous, the nice agreement of the star formation rate measured through the CCSNe rates and that deduced by synthesis modeling for average spiral galaxies, lends support to the general scenario for stellar population evolution. Conversely, the fact that the rate of SN Ia shows no dependence on the galaxy U-V color requires a significant delay between the star formation rate episodes and the onset of SN Ia events. The relation between CCSNe rates and colors provides a useful tool for the comparison of local and high-z SN rates. Indeed, for galaxies at high-z integrated colors can be measured relatively easily, whereas morphological types, requiring superb imaging, are not generally available. Conversely, it is clear that reporting the average SN rates for uncharacterized galaxy samples may turn out to be pointless for constraining galaxy evolution models.

### VIII. SWIFT SOFTWARE

The first software that will be concentrated on will be the HEASARC software. This software primarily focused on the calculation of the total galactic hydrogen column density, which is the mass of hydrogen per unit area integrating volumetric density over a column. Taking the values derived from Soderberg 2008, the calculation of the total galactic hydrogen column density, \( N_H \), for XRO 080109 was dependent on those values derived from Soderberg 2008.

**FIG. 20.**

Calculated \( N_H \) for XRO 080109 using values derived from Soderberg 2008.

The second software that will be concentrated on will be the WebPIMMS software. This software was primarily used to calculate the theorized flux value for XRO 080109 using the Soderberg 2008 values as derived inputs. The calculated flux and unabsorbed flux are shown below.

The third software that will be concentrated on will be the WebSpec software. This software is used as a result and therefore conclusion of the results given from the HEARSARC and WebPIMMS software. WebSpec provides a facility for simulating spectra for a variety of mission/instrument combinations and several different models. It utilizes the X-ray spectral fitting package, XSPEC.
FIG. 21. Process of deriving the counts/second from the given observed flux using the WebPIMMs software.

FIG. 22. Calculated Flux and Unabsorbed Flux for XRO 080109 using values derived from Soderberg 2008.

From this, a plot is produced that contrasts the channel energy used for the selected mission/instrument and contrasts this against the normalized counts/sec/keV. The plot produced itself is a simulated energy spectrum, which is the energy carried by photons at different frequencies. And, the normalized factor is simply the input divided by the effective area of the chosen instrument, which in this case would be the Swift XRT PC Mode (Grades 0-12), using the photoelectric absorption with a power law model in coincidence. The plot demonstrates a slow increase over channel energy, the x-axis, and therefore a decrease at low x-ray energies due to photoelectric absorptions of soft x-rays by the heavy atoms along the line of sight. Displayed below is the plot itself, as well as the produced variables resulting from this plot.
FIG. 25.
Values inputted into WebSpec software for XRO 080109 using values derived from Soderberg 2008.

FIG. 26.
Plot produced for XRO 080109 using values derived from Soderberg 2008 contrasting channel energy against the normalized counts/sec/keV.

FIG. 27.
Process of deriving the counts/second, overall count rate, and minimum flux input needed from the given observed flux using the WebSpec software.

FIG. 28.
Calculated values for XRO 080109 using values derived from Soderberg 2008 from the WebSpec plot produced.
To calculate the needed exposure time for different galaxies at varying distances, for example XRO 080109, the published flux is first needed. For XRO 080109, the Soderberg flux 6.9E−10erg/cm/cm/s was used and became the $F_S$ variable, and $D_{OldDistance}$ was 27 Mpc (which was originally estimated for the distance of XRO 080109 in Soderberg 2008 from the Milky Way.

$$L = F4πD^2 \quad (31)$$

Where $F$ is the flux, and $D$ is the distance measured in Mpc.

$$F_{S,new} = \frac{F_S \cdot (D_{OldDistance})^2}{(D_{NewDistance})^2} \quad (32)$$

And, to account for the redshift present, the equation below is factored into $D_{NewDistance}$.

$$D_L = \frac{\text{size}}{\theta} \cdot (1 + z)^2 \quad (33)$$

$D_L$ is the corrected distance with redshift bias included, size is the transverse extent of an object, theta is the angle (in radians) that the object subtends on the sky, and $z$ is the redshift chosen.

Then, to convert counts per second into exposure time for the Swift/XRT for a source detection goal, the following equation is used:

$$cps \cdot T_{\text{exposure}} = 20cts \quad (34)$$

Cps is the counts per second, and $T_{\text{exposure}}$ is the time of exposure needed for the Swift/XRT.

**IX. EXPANDING PHOTOSPHERE METHOD**

Massive stars come in a wide variety of luminosities and sizes and would seemingly not be useful objects for making distance measurements under the standard candle assumption. However, from a radiative transfer standpoint these objects are relatively simple and can be modeled with sufficient accuracy to measure distances to approximately 10%. The expanding photosphere method (EPM), was developed by Kirshner and Kwan, and implemented on a large number of objects by Schmidt et al. after considerable improvement in the theoretical understanding of type II SN (SN II) atmospheres.

EPM assumes that SN II radiate as dilute blackbodies.

$$\theta_{ph} = \frac{R_{ph}}{D} = \sqrt{\frac{F_s}{\pi \cdot B_\lambda(T)}} \quad (35)$$

where $\theta_{ph}$ is the angular size of the photosphere of the SN, $R_{ph}$ is the radius of the photosphere, $D$ is the distance to the SN, $F_s$ is the observed flux density of the SN, and $B_\lambda(T)$ is the Planck function at a temperature $T$. Since SN II are not perfect blackbodies, we include a correction factor, $\xi$, which is calculated from radiate transfer models of SN II. SNe freely expand, and

$$R_{ph} = v_{ph}(t - t_0) + R_0 \quad (36)$$

where $v_{ph}$ is the observed velocity of material at the position of the photosphere, and $t$ is the time elapsed since the time of explosion, $t_0$. For most stars, the stellar radius, $R_0$, at the time of explosion is negligible, and the two equations can be combined to yield

$$\theta = D \left( \frac{\theta_{ph}}{v_{ph}} \right)^2 + t_0 \quad (37)$$

By observing a SN II at several epochs, measuring the flux density and temperature of the SN (via broad band photometry) and $v_{ph}$ from the minima of the weakest lines in the SN spectrum, we can solve simultaneously for the time of explosion and distance to the SNII. The key to successfully measuring distances via EPM is an accurate calculation of $\xi(T)$.

$$4\pi R^2 \pi B_\lambda(T) = 4\pi D^2 f_\lambda \quad (38)$$

$$\frac{L_B}{L_{B_{MilkyWay}}} = 10^{\frac{M_{MilkyWay} - M_B}{2.5}} \quad (39)$$

$$\theta D = v \Delta t + R_0 \quad (40)$$

$$\Delta t = D \frac{\theta}{v} \quad (41)$$

**X. APPENDIX**

GRB 050509B was the first short GRB noted by Swift that displayed an X-ray counterpart, with a approximate 9 arc second localization. Deep follow up observations conducted failed to reveal optical afterglow but did discover a massive $z=0.225$ elliptical galaxy near the X-ray error circle, with a chance coincidence probability of around $10^{-3}$. It is important to note that if GRB 050509B was indeed $z=0.225$, then the non-detection of a supernova was significant. But, two months later HETE-2 discovered the short gdb 050709. Chandra precisely localized the X-ray afterglow, and follow up observations revealed the first optical afterglow from a short GRB. The first notable observation in 2005 for short GRBs was another Swift discovery, the short GRB 050724, which
resulted in the discovery of X-ray, optical/ near-IR, and the first afterglow emission also demonstrated that both the energy and density were lower than for long GRBs. Therefore, it was concluded that short GRBs are cosmological, as they produced the afterglow emission similar to the long GRBs but with a lower produced energy and density scale. And, thus their progenitor are not massive stars because of their lack of associated supernovas.
<table>
<thead>
<tr>
<th>Telescope (m)</th>
<th>Detector Format (pixels)</th>
<th>Timing Resolution (ms)</th>
<th>Field of View (arcminutes)</th>
<th>Pixel Scale (arcsec per pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5m Wolter 1, 12 Shells</td>
<td>600x600</td>
<td>0.14x1.8</td>
<td>23.6x23.6</td>
<td>2.36</td>
</tr>
</tbody>
</table>

TABLE I. Breakdown of Swift XRT Components

<table>
<thead>
<tr>
<th>Object</th>
<th>Angular Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canis Major Dwarf Galaxy</td>
<td>12°</td>
</tr>
<tr>
<td>Large Magellanic Cloud</td>
<td>10.75°9.17°</td>
</tr>
<tr>
<td>Barnard’s Loop</td>
<td>10°</td>
</tr>
<tr>
<td>Centaurus A</td>
<td>10°.4°</td>
</tr>
<tr>
<td>Coalsack Nebula</td>
<td>7°.5°</td>
</tr>
<tr>
<td>Rho Ophiuchi cloud complex</td>
<td>6.5°.4.5°</td>
</tr>
<tr>
<td>Small Magellanic Cloud</td>
<td>5°.3°</td>
</tr>
<tr>
<td>Simeis 147</td>
<td>3°</td>
</tr>
<tr>
<td>Rosette Nebula</td>
<td>1.3°</td>
</tr>
<tr>
<td>NGC 6357</td>
<td>1°</td>
</tr>
<tr>
<td>Carina Dwarf</td>
<td>23.4° 15.5°</td>
</tr>
<tr>
<td>Messier 5</td>
<td>23° x 23°</td>
</tr>
<tr>
<td>Messier 13</td>
<td>23° x 23°</td>
</tr>
<tr>
<td>Messier 93</td>
<td>22° x 22°</td>
</tr>
<tr>
<td>NGC 300</td>
<td>21.9° 15.5°</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>21.9° 12.3°</td>
</tr>
<tr>
<td>Messier 110</td>
<td>21.9° 11.0°</td>
</tr>
<tr>
<td>NGC 4236</td>
<td>21.9° 7.2°</td>
</tr>
<tr>
<td>IC 342</td>
<td>21.4° 20.9°</td>
</tr>
<tr>
<td>NGC 247</td>
<td>21.4° 6.9°</td>
</tr>
<tr>
<td>Messier 38</td>
<td>21° x 21°</td>
</tr>
<tr>
<td>NGC 6792</td>
<td>20° x 20°</td>
</tr>
<tr>
<td>Trifid Nebula</td>
<td>20° x 20°</td>
</tr>
<tr>
<td>NGC 2264</td>
<td>20° x 20°</td>
</tr>
<tr>
<td>Messier 10</td>
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<tr>
<td>Messier 43</td>
<td>20° x 15°</td>
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<tr>
<td>NGC 4945</td>
<td>20° 3.8°</td>
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<tr>
<td>NGC 3109</td>
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</tr>
<tr>
<td>Messier 55</td>
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</tr>
<tr>
<td>NGC 4372</td>
<td>18.6° x 18.6°</td>
</tr>
<tr>
<td>Messier 106</td>
<td>18.6° 7.2°</td>
</tr>
<tr>
<td>NGC 3201</td>
<td>18° x 18°</td>
</tr>
<tr>
<td>Iris Nebula</td>
<td>18° x 18°</td>
</tr>
<tr>
<td>Messier 3</td>
<td>18° x 18°</td>
</tr>
<tr>
<td>Messier 15</td>
<td>18° x 18°</td>
</tr>
<tr>
<td>Crescent Nebula</td>
<td>18° 12°</td>
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<tr>
<td>Palomar 12</td>
<td>17° x 17°</td>
</tr>
<tr>
<td>Messier 19</td>
<td>17° x 17°</td>
</tr>
<tr>
<td>Messier 2</td>
<td>16° x 16°</td>
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<td>Messier 12</td>
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<td>Messier 50</td>
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<td>NGC 4565</td>
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<td>NGC 6822</td>
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<td>NGC 4631</td>
<td>15.5° 2.7°</td>
</tr>
<tr>
<td>Messier 26</td>
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<tr>
<td>NGC 3628</td>
<td>15° 3°</td>
</tr>
<tr>
<td>Wild Duck Cluster</td>
<td>14° x 14°</td>
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<tr>
<td>NGC 288</td>
<td>13° x 13°</td>
</tr>
<tr>
<td>NGC 891</td>
<td>13.5° 2.5°</td>
</tr>
<tr>
<td>Messier 9</td>
<td>12° x 12°</td>
</tr>
<tr>
<td>Messier 14</td>
<td>11° x 11°</td>
</tr>
<tr>
<td>NGC 6946</td>
<td>11° 10°</td>
</tr>
<tr>
<td>Messier 82</td>
<td>11.2° 4.3°</td>
</tr>
</tbody>
</table>

TABLE II. Angular Sizes of Galaxies within Swift XRT Parameters