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Evaluation of 26Al method as star formation rate indicator

Manjeet Singh
Clemson University, manjees@g.clemson.edu

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EVALUATION OF THE \( ^{26}\text{AI} \) METHOD AS STAR FORMATION RATE INDICATOR

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Physics

by
Manjeet Singh
December 2012

Accepted by:
Dr. Dieter H. Hartmann, Committee Chair
Dr. Mark Leising
Dr. Chad Sosolik
ABSTRACT

The aim of this work is to evaluate the “$^{26}$Al method” used to determine the Galactic Star Formation Rate (SFR) and compare it to other alternative methods. $^{26}$Al is a radioactive isotope produced mainly in massive star winds and in the ensuing core collapse supernova explosion. The radioactive $^{26}$Al decays with a life time of $10^6$ years by emitting $\gamma$- ray photons in 1.808 MeV band. The $^{26}$Al method involves using the Galactic $^{26}$Al radioactive flux as a tracer. This approach based on the $\gamma$- ray line measurements does not suffer from extinction and small number statistics.

To evaluate the $^{26}$Al method, we model the spatial distribution of massive stars by Monte-Carlo methods and simulate the kinematics of radioactive $^{26}$Al produced in massive star winds and supernovae explosions. The wind from a massive star leads to the formation of a hot bubble around the star and we use a wind/ISM interaction model to simulate this interaction of the hot bubble and the ISM. A Supernova explosion inside this wind bubble results in the production of additional $^{26}$Al, the distribution of which is modeled using a supernova expansion model.

Thus, this work builds on the previous work (Diehl et al. 2006) by including the $^{26}$Al contribution from massive star winds to the total budget of the Galactic $^{26}$Al. We find that the results from our simulation are consistent with observations. We conclude that the addition of $^{26}$Al from massive star winds results in a lowering of the estimated SFR by 20%. We further infer that a donut with arms distribution model (free-electron density model of only the thin disk and spiral arms) reflects the real distribution of
Galactic $^{26}\text{Al}$ and we derive a SFR of $\sim 3.5 \pm 1.7 \, \text{M}_\odot \, \text{yr}^{-1}$ which is consistent with Diehl et. Al (2006).

The uncertainties associated with the $^{26}\text{Al}$ method are largely due to uncertainty in the possible sources of $^{26}\text{Al}$ and the yields associated with each source. All other SFR estimating methods suffer from varying degrees of selection affects. There are systematic errors owing to incomplete catalogs, Galactic visual extinction and small number statistics. Thus, the $^{26}\text{Al}$ method is a direct means of deriving the Galactic SFR that is not prone to selection affects.
DEDICATION

To the pursuit of happiness. Looking for my piece of the π.
ACKNOWLEDGMENTS

I am very thankful to my Advisor Dr. Dieter Hartmann and the other members of my committee for their invaluable guidance. I would also like to thank Jane Gan and Jeremy Capps for the support and encouragement.
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INTRODUCTION

Our universe contains billions of galaxies. These galaxies are producers and recyclers of elements. Star forming cores in molecular clouds are like galactic factories producing and recycling elements on timescales ranging from millions to billions of years. The raw material is “trucked in” to these factories by gravity and supernova explosions. Stellar nucleosynthesis produces both stable and unstable elements that get ejected into the interstellar medium (ISM) by stellar winds and supernova explosions. The ISM cools down on a timescale of billions of years forming dense clouds that collapse back to star forming cores and the cosmic element cycle begins again enriching the galaxy with heavy elements.

The unstable elements formed in stellar nucleosynthesis may undergo radioactive decay with different decay life-times giving rise to characteristic γ-ray photons. If these radioactive isotopes are ejected in the ISM before destruction, then γ-ray line spectra from these radioactive decays can be observed and studied. Our universe is transparent to γ-rays. So detection of these γ-ray line photons is a great tool to identify and study the abundance of radioactive isotopes.

Only a small number of radioactive isotopes have lifetimes long enough to be observed in the γ-ray line measurements. $^{26}$Al and $^{60}$Fe are two long-lived radioactive isotopes. Gamma-ray lines from $^{26}$Al and $^{60}$Fe provide a tool to probe the young source populations and test massive star nucleosynthesis models. The diffuse flux is connected to the galactic SNR and eventually to the galactic SFR.
In chapter two we review four methods of determining the star formation rate. All these methods are essentially grounded on the motivation to look for a well understood tracer that could be corrected for observational selection effects. These methods include examination of the historic records of Galactic SNe, determination of the ccSN rate in other galaxies, counting potential supernova remnants and measuring Galactic radioactive $^{26}$Al flux.

In chapter three we introduce the three most important radioactive isotopes: $^{26}$Al, $^{60}$Fe and $^{44}$Ti and review the respective production mechanisms.

In chapter four we discuss the initial mass function (IMF). IMF appears twice in the $^{26}$Al method as the IMF averaged yield and as the IMF averaged mass. Therefore, it is a major source of uncertainty and the right choice for an IMF slope is motivated in this chapter.

Chapter five deals with an in-depth analysis of the $^{26}$Al method. We start by examining the galactic production sites of the $^{26}$Al radioactive isotope followed by a study of the $^{26}$Al yield estimates. Then the massive star distribution and supernova ejecta expansion models are discussed followed by results and a discussion of these results.
CHAPTER 2

STAR FORMATION RATE ESTIMATION METHODS: AN OVERVIEW

The star formation rate (SFR) of the Milky Way is important for any study of galactic evolution. It strongly influences Galaxy formation and evolution by providing energy, momentum, and chemical feedback in the form of stellar winds and supernova explosions. Moreover, it is a key driver of structure evolution in the interstellar medium (ISM) and thus, the SFR is a very important astrophysical quantity. This rate is linked to the core collapse supernova rate (SNR) through an initial mass function (IMF).

The time rate of supernova explosions in the Galaxy is known as the SNR. An understanding of the Galactic supernova rate would lead to a better understanding of stellar evolution specifically, star formation and supernova explosion mechanisms. Supernovae also contribute to the Galactic evolution by releasing chemically processed materials from stars into the interstellar and intergalactic gas. They are almost exclusively responsible for the chemical enrichment of the galaxies and the universe as a whole. Further, supernovae influence kinematics of galaxies by injecting kinetic energy into the ISM. Thus, knowing the supernova rate and in-turn the star formation rate helps us to look back at the chemical history of galaxies and their evolution in time.

In this chapter we give an overview of the basic strategies used to estimate the galactic star formation rate and methods associated with these strategies. We also look at apparent shortcomings of each method. The basic idea behind every strategy to obtain
star formation rate is to look for a well understood tracer that can be corrected for observational selection effects.

2.1 Counting the number of SN events in the Milky Way

Historical Supernova Record

The main idea behind this strategy is to use historical data and count the number of observed supernova explosions in the Milky Way to derive a Galactic supernova rate and hence, a star formation rate. In theory this should work fine. But the number of supernovae observed in last 1000 years is a very small number (The et al., 2006). The last known SNe event was in late 17\(^{th}\) century (See table 2.1). Galactic visual extinction, no doubt, has to be the most prominent reason for this small sample size. Failure in record keeping and loss of historical records due to wars, natural disasters, etc might also have affected the sample size. A total of 6 supernovae in last 1000 years corresponds to a SNR of 0.6 per century a number that is much lower than the common accepted value of ~ 2 events per century. This is definitely a result of incomplete data that leads to very large uncertainties when extrapolated to the full galactic disk. Relative rates of SNe based on type could also be estimated from this sample.

To understand the low SNR estimate from historical supernova method, we simulated half million supernovae using Monte Carlo simulations. Galactic visual magnitude of each supernova at the Sun was calculated based on the galactic visual extinction model of Hakkila et al. (1997). Human eye can only observe stars with an apparent magnitude lower than 6. Thus, only supernovae with an apparent magnitude less than 6 for atleast 3 days were counted as a potential visible supernova event. The
inclusion of Galactic visual extinction leads to an observation rate of only 35% i.e. only 35% of the actual supernova events were observable at the Sun due to visual extinction modeled in the simulation.

If galactic visual extinction is taken as the only reason for small sample size of the observed supernova events in the last 1000 years, then the above historical supernova sample includes only of 35% of the total supernova events during that period. Thus, the actual SNR should be ~ 3 times 0.6 events which is equal to ~1.8 SNe events per century consistent with current estimates.

2.2 Counting the number of events in other galaxies

Van den Bergh & Tammann (1991)

This method involves counting number of supernova events in other galaxies and extrapolating the value to our Milky Way assuming that our galaxy is one of the similar types as the observed galaxies. This method is also a direct counting method like historical SNe method but in this case supernovae events in external galaxies are counted rather than the events in our own galaxy.

Van den Bergh and Tammann (1991) deduce the SN rate in the Milky Way by recording the luminosities and the SN rates of the Milky Way type Galaxies. Studies of the SN rates in external galaxies lead them to a Galactic SNR ~ 4 events per century. The authors defined a SN rate dependent on Luminosity class (the SNR per luminosity) and assumed a Gaussian luminosity function.
This method is not only marred by selection effects but it is also based on a frail assumption that the SN rate is constant among galaxies. Figure 2.1 based on the work by Mannucci et al. (2005) supports the viewpoint that SN rate is different for different galaxy types.
Table 2.1  Recent Galactic Supernova Record

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Longitude (Degrees)</th>
<th>Latitude (Degrees)</th>
<th>Type</th>
<th>Distance (Kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lupus</td>
<td>1006</td>
<td>327.57</td>
<td>14.57</td>
<td>Ia</td>
<td>2.2</td>
</tr>
<tr>
<td>Crab</td>
<td>1054</td>
<td>184.55</td>
<td>-5.79</td>
<td>II</td>
<td>2.0</td>
</tr>
<tr>
<td>3C58</td>
<td>1181</td>
<td>130.73</td>
<td>3.07</td>
<td>II</td>
<td>2.6</td>
</tr>
<tr>
<td>Tycho</td>
<td>1572</td>
<td>120.09</td>
<td>1.42</td>
<td>Ia</td>
<td>2.4</td>
</tr>
<tr>
<td>Kepler</td>
<td>1604</td>
<td>4.53</td>
<td>6.82</td>
<td>IB/II</td>
<td>4.2</td>
</tr>
<tr>
<td>Cas A</td>
<td>1680</td>
<td>2.92</td>
<td>-2.13</td>
<td>Ib</td>
<td>2.92</td>
</tr>
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</table>

Fig 2.1  SN rate per $K$ band luminosity (Mannucci et al., 2005)
2.3 Counting Objects that could be SN remnants

Faucher-Giguère and Kaspi (2006) and Van den Bergh (1990) in this method tracers that could be SN remnants are explored and counted. Most core collapse supernovae (cc SNe) leave behind a pulsar. Detection of these radio pulsars can be used to derive a cc SN rate assuming a supernova to pulsar conversion rate. Another way to count the number of supernovae is to use X-ray and radio observations to peer through the dust and gas, and observe the remains of supernovae. These supernova remnants emerge a few decades after a supernova explosion and last for thousands of years, and are bright in X-rays and radio waves.

Faucher-Giguère and Kaspi (2006) assumed all cc SNe left either a black hole or a pulsar, and derived cc SN rate of ~ 3.2-3.7 per century. The authors based their work on a Galactic pulsar birth rate of ~ 2.8 per century and they ignored the fact that 13% to 25% of cc SNe leave behind a black hole and not a pulsar. Extensive observational selection effects combined with an uncertainty in the ratio of SNe to pulsar conversion renders this method impractical for estimating the galactic SNR.

Van den Bergh (1990) and Van den Bergh and Tammann (1991) both studied Galactic supernova remnants and inferred a supernova rate of $1.5 \pm 0.8$ per century and $3.3 \pm 2$ per century respectively. One problem with these estimates is the small sample size. Only about 250 Galactic supernova remnants are cataloged till date. Another issue pertains to the physics associated with supernova remnants. The essential physics is not understood quite well yet and hence, conclusions based on these remnants should not be taken on face value.
2.4 Measure Flux from Radioactive Nucleosynthesis Output

\textit{26}Al Method

\textit{26}Al is a radioactive isotope produced mainly in massive stars and released into the surroundings by a core collapse supernova explosion. The \textit{26}Al decays with a life time of \(10^6\) years by emitting \(\gamma\)-ray photons in 1.808 MeV band. Our galaxy is transparent to these \(\gamma\)-rays.

The \textit{26}Al method involves using the Galactic \textit{26}Al radioactive flux as a tracer. On average, about \(10^{-4}\) M\(\odot\) (solar masses) of \textit{26}Al is produced in a supernova event which adds up to a few solar masses in the ISM for a mean life of \(10^6\) years. The diffuse flux from this trace element is detected and converted back to mass of radioactive \textit{26}Al in the galaxy. This mass is linked to a supernova rate by an IMF averaged yield and the mean life of \textit{26}Al. The SN rate is connected to a star formation rate (Details in chapter 4).

The IMF and the IMF averaged nucleosynthesis yields are the only uncertain quantities in this method. Studying the 1.8 MeV \(\gamma\)-ray line emission map of the Galaxy can also provide insight into the nature and distribution of the \textit{26}Al sources. From the structure of the emission, alignment of emission maxima with spiral arms and comparison with tracers of candidate \textit{26}Al sources, we learn that \textit{26}Al extends all along the plane of the Galaxy.

The diffuse \(\gamma\)-ray 1.8 MeV emission from galactic \textit{26}Al emission is detected and plotted as a sky map. Thus, this method is most direct and least subject to selection effects.
CHAPTER 3

RADIOACTIVE TRACERS

Unstable radioactive tracers are produced in stellar nucleosynthesis along with other stable nuclei. The life-times of these unstable radioactive isotopes ranges from few seconds to millions of years. Clayton and Craddock (1965) suggested that these unstable nuclei may decay by giving rise to $\gamma$- ray photons. Detection and study of characteristic $\gamma$-ray signature of unstable isotopes with lifetimes shorter than the age of the Galaxy would help us in understanding the nucleosynthesis history and evolution of our galaxy. Three important galactic radioactive isotopes are discussed in this chapter.

3.1 Radioactive Isotope $^{26}$Al

$^{26}$Al in its ground state is unstable to positron emission or to electron capture with a mean life of $10^6$ years. Proton capture on $^{25}$Mg is the primary production mechanism of $^{26}$Al during the neon-oxygen burning phase of stellar evolution (Clayton and Leising 1987). For a significant production of $^{26}$Al, both proton rich and magnesium rich environments are needed. These environments are encountered during hydrostatic H-burning conditions and during explosive burning of carbon and neon shells (Limongi and Chieffi, 2006). A substantial amount of $^{26}$Al is ejected in stellar winds before the explosion and later in SNe ejecta during the explosion.

The transitions from the decay of $^{26}$Al into $^{26}$Mg leads to production of $^{26}$Al emission line at 1.809 MeV. The $^{26}$Al emission line was the first detection of a $\gamma$- ray...
radiation produced by a cosmic radioactive isotope. HEAO-C spacecraft detected 1.809 MeV line in 1982. Decay chain of $^{26}$Al is shown in figure 3.1.

![Decay scheme of $^{26}$Al](image)

**Fig 3.1** Decay scheme of $^{26}$Al

### 3.2 Radioactive Isotope $^{60}$Fe

$^{60}$Fe is an unstable nucleus co-produced with $^{26}$Al with a half-life of $2 \times 10^6$ years. The production mechanism involves explosive oxygen-neon burning and hydrostatic carbon burning. The $^{60}$Fe isotope is synthesized in neutron capture reactions from the $^{56}$Fe isotope. $^{60}$Fe decays to $^{60}$Co with a half-life of 2 Myr with emission of $\gamma$-ray photons at 59 KeV and then immediately decays to $^{60}$Ni by emitting $\gamma$-ray photons at 1173 and 1333 KeV with a half-life of 5.3 yrs (Limongi and Chieffi, 2006). The 59 KeV line flux is very difficult to detect with present missions. Due to its long decay time, $^{60}$Fe survives to be
detected after a supernova ejects it into the interstellar medium. The first detection of $^{60}$Fe lines was made by HEAO-3. The decay chain of $^{60}$Fe is shown in figure 3.2.

![Decay Chain of $^{60}$Fe](image)

**Fig 3.2  Decay Chain of $^{60}$Fe**

### 3.3 Radioactive Isotope $^{44}$Ti

$^{44}$Ti is another short-lived radioactive isotope. It has a mean life of 89 years and is believed to be produced in core-collapse supernovae. $^{44}$Ti decay is understood to be the only source of stable isotope $^{44}$Ca. As $^{44}$Ti has a short decay time scale, its $\gamma$-rays reflect the current supernova explosion rate. There are three $\gamma$-ray lines that could be used to detect the decay of $^{44}$Ti: the 68 and 78 keV lines from the $^{44}$Sc de-excitation cascade and the 1157 keV line as $^{44}$Ca decays to its stable ground state (Wang, 2007). $^{44}$Ti decay chain is shown in figure 3.3.

Wang et. al 2007
The 1157 keV $\gamma$-ray line following $^{44}$Ti decay has been detected inside the 350 year old Cas A supernova remnant. The emission helps to constrain models of ejecta distribution and mixing in the ISM. Unfortunately, only Cas A has been detected with a $^{44}$Ti emission line till date.

Fig 3.3 Decay Chain of $^{44}$Ti
CHAPTER 4
INITIAL MASS FUNCTION

The initial mass function (IMF) describes the number of newly formed stars per mass interval in an embedded star cluster with stellar mass $M_c$ i.e.

$$\xi_{M_c} = \frac{dN_{stars}}{dm}$$

In other words, the IMF $\xi(m)$ specifies the fraction of stars formed with initial stellar mass within the interval $m$ and $m+dm$. $\xi(m)$ is normalized to 1 star in the lower mass interval $m_{\text{low}}$ and upper mass interval $m_{\text{upp}}$:

$$\int_{m_{\text{low}}}^{m_{\text{upp}}} \xi(m) dm = 1.$$ 

The IMF is generally categorized by a log-normal type mass distribution or a segmented power law (Salpeter, 1955; Kroupa, 2001; Chabrier, 2003).

$$\xi(m) \propto m^\alpha$$

Slope estimates range from $\alpha = -2.1$ to $\alpha = -3.4$ (Salpeter, 1955; Massey et al., 1995; Kroupa, 2007; Scalo, 2005). In this work, $m_{\text{upp}}$ is taken to be 120 $M_\odot$ and $m_{\text{low}}$ to be equal to 0.08 $M_\odot$.

Study of the IMF is necessary in understanding the star formation rate. It gives an insight into link between stellar and galactic evolution. The IMF is also essential in interpreting results like supernova rates, mass-to-light ratio and metal enrichment. The IMF is affected by chemical elements from observable universe, chemical feedback and thus, is linked to the evolution of galaxies.
The pioneering work on IMF was done by Salpeter in 1955 (Salpeter, 1955). He assumed formation rate of stars in the solar neighborhood to be constant and considered the IMF to be time-independent and a smooth function of mass. Systematic studies on IMF were done after the seminal work of Salpeter by Miller and Scalo (1979) and Scalo (1986). These studies were based on observations. Recent increase in computational power has led to advances in theoretical understanding of the IMF. Numerical simulations enable us to produce a measurable IMF that could be compared with observations. Kroupa (2002-2007) Chabrier (2004) and Scalo (2005) have used these recent advances in both observation and theory to further explore and constrain the IMF.

Although, all the above studies have improved our understanding of the IMF to a great degree, they are all marred by few issues. Some of the issues are discussed below:

- Studies to search the IMF require the implicit assumption that the IMF is constant over some spatial or temporal scale.
- It is assumed that the IMF does not varies with time (present day mass function (PDMF)).
- Finite stellar lifetimes are assumed.
- Then there is the issue of stellar multiplicity and unresolved binaries.
- Uncertainty in upper bound mass and choice of lower limit for faint stars.
- Dynamical evolution is not taken into account.
In this work, an IMF of slope equal to -2.7 is used. The motivation behind the choice of slope is as follows:

- Metal content of the galaxy cluster is well reproduced by a Salpeter IMF for stars between 1 and 25 M\(_\odot\) (Renzini, 2005).
- High end of the stellar mass spectrum is well approximated by a power law index of -2.35 (Bastain, 2010).
- IMF studies from chemical evolution models imply that high end mass of the IMF has been invariant since a redshift of \(z \sim 3-5\). This is consistent with Salpeter IMF at the high mass end (Becker et al, 2006; Pettini 2008).
- Kroupa (2007) tried to understand non-star formation sources of apparent variations in the IMF. This includes Poisson scatter due to finite number of stars in the sample, loss of stars of a preferred mass-scale as their parent star clusters evolve dynamically and wrong mass estimate due to binary systems. He describes a three part power law for low mass end:
  \[ \alpha = -2.3 \text{ (} m \geq 0.5 \text{)}, \quad \alpha = -1.3 \text{ (} 0.08 < m < 0.5 \text{)}, \quad \alpha = -0.7 \text{ (} 0.01 < m < 0.08 \text{)} \]
  The author further suggests a value of \( \alpha = -2.7 \) for the Milky Way disk.
- Scalo (2005) compiled determinations of the logarithmic power-law index for many clusters and OB associations in the Milky Way galaxy and the Large Magellanic Cloud. He took into account local star-counts together with the assumptions about the Star Formation History, spatial structure of the MilkyWay disk and stellar evolution corrections. He also deduced an IMF value of \( \alpha = -2.7 \).
Even though the slope value varies between -2.1 to -2.7 in most studies, a value of -2.7 is deemed fitting for the relevant mass range of 10 M\(_{\odot}\) - 120 M\(_{\odot}\) in this work. The nature of clustered star formation leads to a galaxy-wide initial mass function (IGIMF) which steepens with decreasing SFR.

4.1: A Look at the mass limits

Observationally the limits on stellar masses are unclear. A lower mass limit of 0.08 M\(_{\odot}\) is used in this work. There is lack of observational evidence for stars above 150 M\(_{\odot}\) (Weidner and kroupa, 2004; Figer, 2005). In this work, an upper mass of 120 M\(_{\odot}\) is used. Table 4.1 shows how normalization constant (a), mean mass (<m>) and the fraction of massive stars that become supernovae (f\(_{\text{sn}}\)) vary for two different upper mass values of 120 M\(_{\odot}\) and 150 M\(_{\odot}\). It can be seen that a, <m> and f\(_{\text{sn}}\) are almost similar for both mass limits. Thus, an upper mass limit of 120 M\(_{\odot}\) is used in this project as it is consistent with other research works.

<p>| Table 4.1 | Variation for m(<em>{\text{upp}}) = 120 M(</em>{\odot}) and 150 M(_{\odot}) |
|-----------|------------------|---------------|----------------|</p>
<table>
<thead>
<tr>
<th>Upper Mass (M(_{\odot}))</th>
<th>α</th>
<th>A</th>
<th>&lt;m&gt;</th>
<th>f(_{\text{sn}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-2.1</td>
<td>0.040</td>
<td>0.189</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>-2.3</td>
<td>0.026</td>
<td>0.088</td>
<td>0.0009</td>
</tr>
<tr>
<td></td>
<td>-2.35</td>
<td>0.0236</td>
<td>0.074</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>-2.7</td>
<td>0.01</td>
<td>0.023</td>
<td>0.0001</td>
</tr>
<tr>
<td>120</td>
<td>-2.1</td>
<td>0.04</td>
<td>0.184</td>
<td>0.0027</td>
</tr>
<tr>
<td></td>
<td>-2.3</td>
<td>0.026</td>
<td>0.087</td>
<td>0.0009</td>
</tr>
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</tr>
<tr>
<td></td>
<td>-2.7</td>
<td>0.01</td>
<td>0.023</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
CHAPTER 5

$^{26}\text{Al}$ METHOD

The main idea behind the "$^{26}\text{Al}$ method" is the conversion of the observed $\gamma$-ray line flux from Galactic $^{26}\text{Al}$ to the corresponding supernova rate (SNR), and consequently to the average star formation rate (SFR) (Diehl et al., 2006). Mahoney et al. (1982) made the very first detection of the $^{26}\text{Al}$ $\gamma$-ray line at 1.8085 MeV. The COMPTEL all sky survey launched in 1991 to map the 1.809 MeV distribution clearly suggested that the $^{26}\text{Al}$ emission extends along the galactic plane and thus, production of the radioactive isotope $^{26}\text{Al}$ is a Galactic phenomenon. INTEGRAL mission was designed next with a goal to study 1.809 MeV $\gamma$-ray line emission from kev to Mev range. The INTEGRAL spectrometer (SPI) with an energy resolution of 2.5 keV at 1.3 MeV and angular resolution of 2.5° within a field of view of 16°×16° allows for a high spectral resolution of 2.5 keV at 1 MeV, suitable for astrophysical studies of individual $\gamma$-ray lines and their shapes.

From our simulation, we construct a detailed sky map of the Galactic $^{26}\text{Al}$ line using a spatial distribution model. A comparison is made between this theoretically obtained sky map and the observed sky map. The integrated $^{26}\text{Al}$ flux obtained from the simulation is converted to the total mass of the $^{26}\text{Al}$ isotope in the galaxy. This galactic mass is related to the cc SN rate by the formula:

$$M_{^{26}\text{Al}} = \text{SNR} \times \tau \times \gamma$$

where $\tau$ is mean life of $^{26}\text{Al}$ isotope in years and $\gamma$ is IMF averaged $^{26}\text{Al}$ yield in units of solar mass per supernova.
This supernova rate can be converted to a galactic star formation rate by using the equation:

$$\text{SFR} = \frac{SNR \cdot \langle m \rangle}{f_{sn}}$$

Here $\langle m \rangle$ is the average mass in a star formation event and $f_{sn}$ is the fraction of all stars that become supernova.

The accuracy of this method depends on average yield per supernova which is uncertain and on the possibility of other $^{26}$Al candidate sources. Also, the fraction of cc SNe is not well known. Note that both the average yield and the fraction of cc SNe further depend on the IMF, the accuracy of which is also a matter of debate. But largely, this method is devoid of any selection effects and is a fairly accurate means of measuring the galactic SFR compared to other methods. In this chapter, the “$^{26}$Al method” is discussed and a theoretical model to understand and explain the $^{26}$Al all sky map is developed and discussed in all its gory detail.

### 5.1 $^{26}$Al Production sites

The main production mechanism of $^{26}$Al is proton capture on $^{25}$Mg in a sufficiently hot environment. Proton rich and magnesium rich environments with suitably high temperatures are needed for an effective production of $^{26}$Al. These conditions are encountered in core H burning, the C and Ne convective shells, and the explosive Ne burning. Clayton (1994) discussed the possibility of $^{26}$Al production by nuclear reactions of low-energy heavy cosmic rays in the ISM.
To be observable in the γ-ray band, the freshly synthesized $^{26}\text{Al}$ has to be ejected and convected away from the hot inner burning region into the ISM before destruction. This is mainly possible in explosive sites and in objects suffering extensive mass loss and sufficient internal mixing. These candidates include core-collapse supernovae, novae, Wolf-Rayet (WR) stars, asymptotic giant branch (AGB) stars and cosmic-ray nuclear reactions in the ISM. The most important candidate sites are discussed in the subsequent sub-sections.

5.1.1 Core Collapse Supernovae

Stars more massive than ~ 10 $M_\odot$ end up as core-collapse supernovae. $^{26}\text{Al}$ is produced and ejected during the late pre-supernova phase in stellar winds driven by radiation pressure and in the ensuing supernova explosion. The $^{26}\text{Al}$ yields are dependent on initial mass but in general, the explosive $^{26}\text{Al}$ yields are higher compared to the pre-supernova yields (Limongi and Chieffi, 2006). Yields from cc SNe range from $2 \times 10^{-5}$ $M_\odot$ to $5 \times 10^{-4}$ $M_\odot$ (Limongi and Chieffi, 2006).

Production of $^{26}\text{Al}$ in a massive star/supernova can be broadly divided into two phases:

- A pre-supernova phase: where the $^{26}\text{Al}$ is synthesized in the carbon-neon (C/Ne) convective shell. This happens just prior to the supernova explosion.

- Explosive phase: occurs when the stellar core collapses and the inner core is heated to a temperature of 2-3 billion degrees by an outgoing shock wave. $^{26}\text{Al}$ is produced during explosion at this high temperature. The larger the initial mass
of the massive star, the larger the amount of $^{26}$Al that survives the explosion (Limongi and Chieffi, 2006).

The $^{26}$Al yield increases with increasing initial stellar mass. Initial metallicity of the progenitor star also affects the $^{26}$Al production (Prantzos and Diehl, 1996).

5.1.2 Novae

Novae outbursts commonly achieve temperature conditions that are required for $^{26}$Al production. Convection plays a crucial role in carrying $^{26}$Al to the cooler outer layer of the novae envelope. The production of $^{26}$Al in novae is very sensitive to the initial composition of the envelope and to the nuclear reaction rates. The mass of $^{26}$Al ejected by novae depends inversely on the mass of underlying white dwarf. But low mass white dwarfs are expected to be CO white dwarfs which are insignificant producers of $^{26}$Al. The predicted contribution of radioactive $^{26}$Al from novae is expected to range between 0.1$M_\odot$ – 0.4$M_\odot$. Therefore, we conclude that novae are not the dominant sources of $^{26}$Al in our Galaxy.

5.1.3 Wolf-Rayet Stars

Wolf-Rayet stars produce $^{26}$Al in stellar winds. These stars are the main emitters of $^{26}$Al in the ISM before supernova explosions. Large amounts of $^{26}$Al are produced during hydrostatic core H burning by main sequence stars. At central H exhaustion, the $^{26}$Al is located in the He core and in the region of variable H left behind by the receding convective core.
Mass loss in stars with masses between $10 \, M_\odot$ and $35 \, M_\odot$ is weak as the dredge-up episode does not enter He core. But stars more massive than $35 \, M_\odot$ show substantial mass loss through stellar winds. Thus, the WR stars eject large amounts of $^{26}\text{Al}$ in the ISM in stellar winds. A higher initial mass of the WR star corresponds to a higher $^{26}\text{Al}$ production. The average yield for stars between $10 \, M_\odot$ and $35 \, M_\odot$ is of the order of $10^{-5} \, M_\odot$ and $10^{-4} \, M_\odot$ for stars above $35 \, M_\odot$ (Limongi and Chieffi 2006).

### 5.1.4 Cosmic Ray Interaction

Clayton (1994) suggested that the nuclear reaction of low energy heavy cosmic ray particles could be another efficient $^{26}\text{Al}$ source process. The estimation for Orion region corresponds to a $^{26}\text{Al}$ yield of $\sim 10^{-4} \, M_\odot$. But the Galactic yield is quite uncertain and the process is not significant as a Galactic $^{26}\text{Al}$ source.

### 5.2 $^{26}\text{Al}$ Yield Estimates

$^{26}\text{Al}$ production for different candidate sources has been estimated by various groups. The $^{26}\text{Al}$ yield estimates from massive stars are compiled as a function of initial mass in figure 5.1 (Diehl et al. 2006). All estimates involve production of $^{26}\text{Al}$ in core and shell hydrogen burning phases during stellar evolution and in the O/Ne shell of the pre-supernova star and during the subsequent supernova explosion.

In the figure, type II supernova yields are from Woosley and Weaver (1995). The authors handled treatment of convection by coupling a large reaction network with time dependent convection during pre-supernova evolution. Langer et al. (1995) and Meynet
et al. (1997) estimate the $^{26}$Al yields from WR stars. The two models differ in the treatment of convection and mass loss but both models agree well on the higher mass side of spectrum. Palacios et al. (2005) examined wind contribution from rotating and non-rotating Wolf-Rayet (WR) stars and computed models for initial stellar masses ranging between 25 M$_{\odot}$ and 120 M$_{\odot}$.

In this work we have used $^{26}$Al yields from Limongi and Chieffi (2006). The authors have presented contributions of the wind, the C convective shell, and the explosive Ne/C burning to the total $^{26}$Al yield for solar metallicity stars ranging in mass between 11 M$_{\odot}$ and 120 M$_{\odot}$. For different initial masses, they suggest a higher explosive $^{26}$Al yield than pre-supernova yield (Figure 5.2) and estimate the total $^{26}$Al yields from cc SNe to be between $2 \times 10^{-5}$ M$_{\odot}$ to $5 \times 10^{-4}$ M$_{\odot}$.

![Fig 5.1 $^{26}$Al yield estimates from different studies as a function of initial mass](Diehl et al. 2006)
Fig 5.2 $^{26}$Al yields in different processes (Liongoi and Chieffi, 2006)

5.3 Massive star distribution models

Our simulation produces a theoretical picture of the $^{26}$Al emission in the Galaxy by combining a massive star distribution model with a supernova ejecta expansion model. Understanding the radial distribution and velocity profile of $^{26}$Al ejected in stellar winds and supernova explosions is the key to understand the all sky flux distribution of radioactive Galactic $^{26}$Al and hence, the Galactic star formation rate. Our goal is to combine the massive star distribution model and a supernova expansion model to produce a theoretical picture of $^{26}$Al emission on the sky. So our simulation should take into account the spatial distribution of massive stars in the galaxy, emission and propagation of $^{26}$Al in stellar winds and propagation of explosive $^{26}$Al after the supernova explosion.
Following two models have been used to approximate the massive star forming regions of the Milky Way in this work:

5.3.1 Doughnut Distribution

There is a prominent molecular hydrogen ring at a radius of 5 kpc almost halfway between the Sun and the Galactic center. This feature dubbed as the 5 Kpc ring is the hotbed of most of the Galaxy’s star formation activity. It is a tremendous reservoir of material for the formation of new stars and clusters. Therefore, a large part of supernovae remnants, Galactic HII regions, far- infrared luminosity and diffuse ionized gas are associated with the ring. This ring dominates both the star-formation activity in the Milky Way and the molecular interstellar medium and definitely plays an important role in the dynamics, structure, and evolution of our Galaxy.

A simple doughnut shaped distribution can be used to approximate this 5Kpc ring. A Monte Carlo simulation generates a density profile that is Gaussian in R. The density peaks at 4 kpc with a Gaussian width of 2 kpc. Density as a function of z coordinate is approximated by an exponential function with a latitudinal scale height. This model is pictured in figure 5.3.

5.3.2 Doughnut with Arms

A doughnut distribution is a simple approach to model the distribution of massive stars in our galaxy. But Milky Way has spiral arms and these arms are also composed of millions of individual stars. Therefore, a correct massive star distribution model cannot be obtained without inclusion of spiral arms.
All massive stars form as a result of collapsing giant molecular clouds that are composed primarily of hydrogen gas. Therefore, the HII regions are a good tracer of recent and on-going star formation. Taylor and Cordes (1993) suggested a distribution model using pulsar dispersion measures to map out the distribution of free electrons in the galaxy. Dense regions of ionized HII gas which are also regions of massive star formation are mapped by regions with high density of free electrons.

To model this density distribution, a smooth axisymmetric component that is Gaussian in R is plotted (same as the above doughnut distribution) along with a spiral arm component that is not axisymmetric. The density of the smooth component peaks at 4 kpc and the width of the Gaussian is 2 kpc. To describe spiral arms of the Milky Way, fiducial points for the spiral arms given by Taylor and Cordes (Table 5.1) are plotted and then a interpolation function is described by curve fitting. The spiral arms contain half of the total massive stars shared equally among all four arms. Each arm is given a thickness of 1 kpc by introducing a correction factor. This model is depicted in figure 5.4.

Fig 5.3  Donut distribution in x-y plane.
### Table 5.1

**Coordinates of Fiducial Points Defining Shapes of the Model Spiral Arms**

<table>
<thead>
<tr>
<th>Arm 1</th>
<th>Arm 2</th>
<th>Arm 3</th>
<th>Arm 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$ (kpc)</td>
<td>$r$ (kpc)</td>
<td>$\theta$ (kpc)</td>
<td>$r$ (kpc)</td>
</tr>
<tr>
<td>164°</td>
<td>3.53</td>
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<td>3.76</td>
</tr>
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</tr>
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</tr>
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<td>7.29</td>
</tr>
<tr>
<td>330</td>
<td>5.81</td>
<td>288</td>
<td>8.20</td>
</tr>
</tbody>
</table>

**Fig 5.4** Donut with arms distribution in x-y plane.
5.4 $^{26}$Al Distribution model

To understand how far $^{26}$Al ejecta will travel from its origin and how fast it is travelling, we divide our model in two main parts. First part deals with tracking $^{26}$Al synthesized in a massive star and ejected as wind. This is done by studying wind-ISM interaction. Second part focuses on propagation of explosive $^{26}$Al embedded in the supernova remnants. The remnants expand within the surrounding wind bubble and later in the ISM.

5.4.1 Wind-ISM Interaction

A star with mass lower than 35 $M_\odot$ starts expelling $^{26}$Al in winds as soon as it enters RSG (red supergiant) phase. On the other hand, stars in the upper mass limit (> 35 $M_\odot$) start to eject $^{26}$Al in winds only when they become a WR (Wolf-Rayet). This happens when the total mass of the star reduces enough that layers processed by H-burning are exposed to the surface. RSG phase lasts for $10^5$ years (Dwarkadas 2005) while time spent in the WR phase is taken from Limongi and Chieffi (2006) after which star explodes as a supernova. The $^{26}$Al yield from wind contribution is a function of initial mass and taken from Limongi and Chieffi (2006).

Wind initially expands unopposed in the ISM for about 200 years with a velocity greater than escape velocity $V$ after which swept-up mass of the interstellar medium becomes comparable with the mass in the wind. During free expansion phase, the wind bubble reaches a radius of

$$r = 8.8 \times 10^{17} \times \dot{M}_{-5}^{1/2} \times n_{-1,0}^{-1} \times V_{-1/2,0,3}^{-1/2} \text{ cm}$$
where $\dot{M}$ is the mass loss rate in units of solar masses per year and $n_0$ is the density of the surrounding medium in units of cm$^3$. Wind velocity is in units of km s$^{-1}$ (Ramirez et al. 2006).

Mass of the swept-up material is much larger and in a cooler state than that in the hot wind. As a result, the swept-up material lies in a compressed region. This compressed region expands as long as the star is able to sustain a strong wind. If most of the swept-up material is assumed to remain in a thin shell, then expansion is described by

$$\frac{d}{dt} [M_s(t) \times v(t)] = 4\pi r^2(t)p$$

where $M_0$ is the mass of the swept up material $= \frac{4}{3} \pi r^3(t)n_0$, and $p$ is the internal pressure of the compressed region (Castor et al. 1975).

The wind bubble derives its energy from the wind. Stellar winds add energy at a rate

$$L(t) = \frac{1}{2} \frac{d}{dt} [M(t) \times V^2]$$

Therefore,

$$\frac{dp}{dt} = \frac{L(t)}{2\pi r^3(t)}$$

Above two equations give the swept up mass shell expansion rate,

$$r_{shell} = \left( \frac{L}{14\pi n_0} \right)^{1/5} t^{3/5} m$$

Thus, the interaction between stellar wind and the ISM leads to the formation of a wind bubble surrounded by a thin shell. The shell keeps expanding with constant velocity until the star explodes as a supernova. All the $^{26}$Al ejected in the wind is embedded in the
thin shell in our simulation. A rough estimate of shell velocity can be obtained by using
velocity = (radius of the shell)*(time spent in RSG or WR phase).

5.4.2 Supernova-Bubble/ISM Interaction

The first stage of supernova remnant evolution is one of free expansion. Supernova remnant expands freely with a velocity of about 10000 km s$^{-1}$ for about 200 years within the freely expanding windblown bubble. The second stage of remnant evolution is one of adiabatic expansion. The expanding remnant starts encountering resistance from the windblown bubble shell and the ISM. If the supernova is assumed to be a point source expanding with spherical symmetry, then the point release of a large amount of energy into static surroundings (windblown bubble) produces a blast wave that expands according to Sedov-Taylor formula. The supernova remnant is allowed to expand for a randomly chosen age between 0 and 10 million years.

The radius of blast wave or forward shock as a function of remnant age ($tr$) is given by Truelove and McKee (1999):

$$r_s = 1.54 \times 10^{19} \times n_0^{-0.2} \times \left(\frac{tr}{1000}\right)^{\frac{2}{5}} \text{ cm}$$

The initial rapid expansion of gas leads to bunching up of matter ahead of it. This forms a shell which expands with a velocity given by

$$v_s = 1950 \times n_0^{-0.2} \times \left(\frac{1000}{tr}\right)^{\frac{3}{5}} \text{ Km s}^{-1}$$

and radius given by equation (5.4.2.1) (Truelove and McKee, 1999). The shell expands for the remnant age 'tr' or till the shell velocity remains greater than 20 km s$^{-1}$.
Explosive $^{26}$Al yield is also dependent on the initial mass of the star and is taken from Limongi and Chieffi (2006). Decay is calculated for the $^{26}$Al produced in the supernova explosion and the un-decayed $^{26}$Al remaining in wind bubble separately. The remaining $^{26}$Al in both cases is distributed into 10,000 bullets on their respective shells and the coordinates of each piece of shell are calculated.

5.4.3 Flux Calculation

1.8 MeV line flux generated by each piece is obtained by using

$$ F = \frac{M_{26}}{26(amu) \times \tau_{26} \times 4\pi \times D^2} $$

which is roughly equal to

$$ F = 1.5 \times 10^{-4} \times \frac{M_{26}/M_\odot}{D/(8.5\, Kpc)^2} $$

where $M_{26}$ is the mass of $^{26}$Al piece in solar masses, $\tau_{26}$ is the mean life of $^{26}$Al, $D$ is the distance from Sun in units of 8.5 Kpc and flux $F$ is in units of $\gamma/(cm^2s)$.

Flux from all the ejecta pieces can be combined to obtain the total 1.8 MeV $\gamma$-ray flux and an all-sky plot of $^{26}$Al emission throughout the Galaxy.
5.5 Results

The $^{26}$Al method involves detection of $\gamma$-ray lines from radioactive isotopes ejected in massive star winds and core collapse supernovae. The comparison between results from simulation and observations would help up us to constrain the origin and distribution of radioactive Galactic $^{26}$Al. We can also probe the dynamics of the $^{26}$Al ejected in massive star winds and in the supernova explosions along with the $^{26}$Al intensity and line shapes.

In this chapter we will discuss the results from the theoretical model presented earlier and a comparison of these results with observations.

5.5.1 All Sky Maps

The theoretical model discussed in this work is used to generate the Galactic $^{26}$Al all sky maps. These maps can be compared with the COMPTEL images of $^{26}$Al emission or more recently with the all-sky image of $^{26}$Al from SPI data. Galactic $^{26}$Al is produced in massive star winds and in the ensuing SN explosions and thus, $^{26}$Al all sky maps provide an insight into the massive star distribution geometry and the star formation rate.

SPI has a spatial resolution of 2.7° at energies of 1.8 MeV. This high resolution enables an exploration of $^{26}$Al line shapes in different regions along the galactic plane. Figure 5.5 presents an all-sky image of $^{26}$Al emission obtained with the 3-year SPI data (Halloin et al., 2007). Extended $^{26}$Al emission along the inner Galaxy is clearly visible. The bright emission between 90° and 135° (degrees) corresponds to Cygnus region.
Fig 5.5 The all-sky imaging of $^{26}$Al emission (1805 - 1811 keV) with 3-year SPI Data (Halloin et al., 2007).

$^{26}$Al all sky maps generated from theoretical simulation for two different massive star distributions are presented in figures 5.6 and 5.7. Colors represent intensity with yellow being the greatest, then red, light green and green. In figure 5.6, emission is concentrated in the inner Galaxy and the obvious difference between figure 5.5 and 5.6 is the incompleteness of the map which is due to lack of spiral arms in the donut model.

Figure 5.7 represents a more realistic distribution of the $^{26}$Al emission. The emission is concentrated in the Galactic plane and features from spiral arms are clearly evident similar to the observed sky map (fig 5.5).
Fig 5.6 $^{26}$Al 1.8 MeV all sky map from donut distribution

Fig 5.7 $^{26}$Al 1.8 MeV all sky map from donut with arms distribution
Thus, figure 5.7 is evidently a better simulation of the all sky map from SPI. Hence, a donut with spiral arms geometric distribution is a better model to simulate and understand the emission of $^{26}$Al in our galaxy.

5.5.2 1.8 MeV Emission Profile along the Galactic Plane

$^{26}$Al intensity distribution along the Galactic longitude from 3 year SPI data is presented in Figure 5.8 (Wang 2007). Bulk emission is concentrated in the inner Galaxy, specifically, between 30° and -30° longitude. Spiral arms account for the remaining emission. The relative increase in intensity between ~80° and 120° is associated with Cygnus region.

Fig 5.8  $^{26}$Al intensity distribution along the Galactic longitude (Wang 2007)
Observations from SPI confirm the dominance of massive stars and supernovae as $^{26}\text{Al}$ progenitors. The $^{26}\text{Al}$ intensity profile obtained from the theoretical model is plotted in figure 5.9. A comparison between figures 5.8 and 5.9 corroborates the dominance of the inner Galaxy as the $^{26}\text{Al}$ flux emitter. The intensity profile in figure 5.9 peaks around 0° longitude followed by a fall in intensity on both sides consistent with the SPI spectra. Also, the simulated intensity map successfully replicates the prominent emission feature around 90° and other minor features around 170°, 100° and 130° longitudes that are owing to the spiral arms.

From a comparison study between figures 5.8 and 5.9, we can safely conclude that the donut with spiral arms model is a more realistic geometrical model that is consistent with observations. In theory, by tweaking scale heights and/or supernova expansion model we should be able to exactly replicate maps and plots from SPI observations given that we have a reasonable massive star geometric distribution model.
Fig 5.9  Differential flux vs longitude from simulation

(df/dl is in units of $10^{-4}$ ph s$^{-1}$ cm$^{-2}$ rad$^{-1}$ and Longitude is in degrees)
5.5.3 $^{26}$Al Galactic Spectra

In this subsection, we derive the $^{26}$Al Galactic line spectrum and compare results from simulations with observations. We would also try to understand the role of galactic rotation and average ejecta expansion velocities in Doppler broadening of the $^{26}$Al line spectra.

Consider a spherically symmetric layer that is expanding at a velocity $v=\nu(r)$ and emitting a spectral line with rest frequency $\nu_0$. The sum of emerging intensities over all lines of sight gives total flux emerging from the layer.

$$ F_\nu = 2\pi \int_0^r l_\nu(y) y \, dy $$

where $y$ is the transverse coordinate perpendicular to the line of sight.

This integration is done over the area $2\pi r^2 \sin\theta \cos\theta d\theta$ and the argument of the function has the width $2\nu_0 \nu/c$. The emerging flux does not depend on the frequency and thus, the line contour is rectangular. This result is derived for a layer $dr$ that is expanding in an optically thin medium. Two examples of the flat top rectangular line profile generated from an expanding supernova shell are presented in figure 5.10. If the emitting shell is situated far from the center, we get a double peaked line profile presented in figure 5.11.

Spherically expanding plasma also generates a double peaked profile. The spherical plasma region emits line radiation that are broadened by Doppler broadening due to thermal motion of the electrons and Stark broadening due to the interaction of the ions with the electric fields of neighboring ions and electrons in the plasma. Expansion
velocities of the emitting ions also introduce an additional broadening mechanism to the line profile.

We add the flux emitted from all expanding SNe shells and estimate a total Galactic $^{26}\text{Al}$ line width of $0.4 \pm 0.2$ KeV for both donut and donut with arms geometrical distribution using a Gaussian fit (shown in figure 5.11). Both Galactic differential rotation and random motions of ejecta in the ISM contribute to the $^{26}\text{Al}$ line broadening. Line width of 0.4 KeV corresponds to an average ejecta velocity of about 30 Km s$^{-1}$ which falls within the acceptable range. Galactic differential rotation also leads to a small blue shift of $\sim 0.2$ KeV. We also infer that the $^{26}\text{Al}$ line width remains same for different massive star geometrical distribution models as long as the background model remains same. Thus, the observed $^{26}\text{Al}$ line broadening could be explained by Galactic rotation and modest ejecta velocities.

![Theoretical line profiles for two different expanding spherical shells.](image)

Fig 5.10  Theoretical line profiles for two different expanding spherical shells.
Fig 5.11  Theoretical line profile from aspherically expanding plasma.

Fig 5.12  $^{26}\text{Al}$ energy spectra from the inner Galaxy (Arms with donut model)
5.5.4 $^{26}$Al Line Shapes for Different Longitudes along the Galactic Plane

In this section, we split our sky map into different longitude bins and directly derive the $^{26}$Al line spectra in these regions and investigate for asymmetries. We first divide the sky map obtained from the donut with arms distribution model into two regions of interest: $-60^\circ < \text{lon} < 0^\circ$ (the 4th quadrant) and $0^\circ < \text{lon} < 60^\circ$ (the 1st quadrant) and determine the $^{26}$Al line spectra in these regions simultaneously. The output spectra are displayed in figure 5.12.

The $^{26}$Al line flux in the 4th quadrant is higher than the flux in the 1st quadrant, and the flux ratio is ~ 1.48 which is consistent with the observed flux ratio of $1.3 \pm 0.2$ obtained from SPI data (Wang et al. 2009). The 4th quadrant shows a blue-shift of 0.16 KeV while a redshift of 0.13 KeV is obtained for the 1st quadrant. This red-shift is consistent with the observed red-shift of $0.07 \pm 0.10$ KeV derived from SPI data while the theoretical blue-shift is slightly lower than the observed blue-shift of $0.41 \pm 0.07$ KeV.

![Fig 5.13 $^{26}$Al Spectra for 1st and 4th quadrants.](image)
We further split the sky model into 20° longitude bins along the Galactic plane and derive $^{26}$Al line spectra, line widths and $^{26}$Al line centroid shifts. This allows us to identify the line shifts from bulk motion such as expected from large-scale Galactic rotation, and the study of line broadenings gives a hint about increased $^{26}$Al velocities in particular regions. Figure 5.14 presents the $^{26}$Al line energy shifts for 20° longitude bins along the Galactic plane.

![Graph showing $^{26}$Al line energy shifts along the Galactic plane.](image)

**Fig 5.14** $^{26}$Al line energy shifts along the Galactic plane

The higher blue-shifts for negative longitudes are consistent with observations (0.4-0.8 KeV) from SPI but the red-shifts for negative longitudes are little higher than red-shifts obtained from SPI observations (0.1 keV). The positive and negative longitude asymmetry in the $^{26}$Al line energy shift is consistent with observations. The more pronounced blue-shifts for negative longitudes obtained from simulation is most likely due to unevenness in the supernova distribution because of the orientation of spiral arms around the donut shaped molecular ring.
The $^{26}$Al line widths along the Galactic plane with 20° longitude bins are displayed in figure 5.15. The line broadening of ~ 0.4-0.5 KeV obtained from the simulation is consistent with both Galactic rotation and slight average ejecta velocities (~30 km s$^{-1}$). The longitude region between 20° and 40° shows additional line broadening. This slight increase in line broadening reflects a more recent supernova activity in this region compared to other regions. We also infer that the $^{26}$Al line width remains same for different geometrical models as long as the background model remains same.

![Graph showing 26Al FWHM Variation along the Galactic Longitude](image)

**Fig 5.15** $^{26}$Al FWHM Variation along the Galactic Longitude

### 5.5.4 Donut vs Arms

If supernova events are distributed equally between donut and arms (50% in donut and 50% in arms), then the flux emission from arms exceed the emission from donut by 1.5 - 2 times. Results from three sample simulations are presented in table 1 (appendix 2).
While donut component is directly in front of our Sun, the galactic arms surround our Sun and are much closer. This is the reason for higher flux estimate from arms.

We also ran three separate simulations that differed only in the distribution of supernovae events between donut and arms. The resulting flux profile is presented in figure 5.16. An important characteristic of figure 5.16 is the similarity in the shapes of overall flux profiles from all three geometric distributions. The sample run with 75% of total supernovae events distributed in arms generates a higher flux in outer Galactic regions (> ± 60°) compared to other model distributions. Likewise, the run with 75% of total supernovae events scattered within the donut results in a higher flux within inner Galactic regions as expected. Thus, the longitude profiles from all three simulation runs show similar features and characteristics; the only difference being a modest shift of all three profiles in flux space.

Also, the $^{26}$Al flux brightness appears asymmetric for the left and right side of the Galaxy. The right side is slightly brighter than the left as could be inferred from table 2 in appendix 2.
Fig 5.16  Flux vs Longitude for different supernova concentrations in the Galactic donut and the Galactic arms

Fig 5.17  $^{26}$Al Spectra Along the Galactic Plane (From Simulation)
5.5.5 Latitude study: Point SNe vs SNe with Expanding Ejecta

To explore the effect of the supernova expansion model on the $^{26}$Al emission latitude, we simulated and compared two cases: In the first case supernovae were treated as point sources whereas in the second case the ejecta from the supernovae were allowed to expand according to the supernova expansion model discussed in this work. First simulation run resulted in an average latitude width of $\sim 6^\circ$. After the inclusion of supernova expansion, the average latitude width increased to $\sim 8^\circ$. Thus, the ejecta from supernovae causes $^{26}$Al emission latitude to puff up but the amount of puffiness, of course, depends on the supernova expansion model used.

As discussed above, the expanding ejecta causes a broadening of approximately $2^\circ$ in latitude width in our simulation and the average ejecta velocity (sum of velocities of all ejecta bullets divided by the total number of bullets) from a complete simulation run turns out to be $\sim 30$ Km s$^{-1}$. This seems like a low value for average ejecta velocity at first but it should be noted that the average is over few million years and most supernovae cool down within few hundred thousand years of exploding.

Hence, the $2^\circ$ broadening of latitude in second case could be attributed to an average ejecta velocity of $30$ Km s$^{-1}$. This correlation gives another way of fine tuning the theoretical model.
5.5.6 Sources of Uncertainty

a) Statistics: 5%.

If all the variables in the simulation are kept constant and the simulation is run multiple times, the results in this work fluctuate by ~ 5% which is the statistical uncertainty associated with our simulation.

b) Observed Flux : 3%.

The observed $^{26}$Al Galactic flux is estimated to be within $2.9 \pm 0.1 \times 10^{-4}$ ph cm$^{-2}$s$^{-1}$rad$^{-1}$ (Wang et. Al 2009). If the value of the $^{26}$Al flux in our simulation is varied within the above range, the SNR varies by ~ 3%.

c) Scale height : 2%.

Latitudinal scale height introduces only a small uncertainty even when we vary the scale height between 50 and 150 pc. Thus, scale height is not a major source of uncertainty.

d) Distance of Sun from Galactic Center: 3%.

The exact distance of Sun from Galactic center is still uncertain and actively debated. Majaess, D (2010) estimates the distance to be $8 \pm 0.6$ Kpc based on OGLE RR Lyr variables observed in the direction of the bulge. We observe an uncertainty of 3% in our simulation if we shrink or expand our galaxy in sync with the observed value of the Sun’s distance from Galactic center as per Majaess, D.

In comparison, changing the distance of the Sun from the Galactic center while keeping other Galactic variables constant, results in a much higher uncertainty of ~ 25%.
e) $^{26}$Al Yields: 50%

Diehl et. Al (2006) obtained the $^{26}$Al yield per massive star by using the nucleosynthesis yields from models and averaging them over a high mass Scalo initial mass function. The authors estimate a $^{26}$Al yield of $1.4 \times 10^{-4}$ M$_{\odot}$ per massive star with an uncertainty of 50% based on different published yields as a function of various initial masses. They attribute the uncertainty to complications in stellar structure and burning shells and their dependency on stellar masses. The treatment of stellar rotation and mass loss in different models add further complexity to the problem. Another important and much debated source of uncertainty are the Nuclear-reaction uncertainties specially, the neutron capture reactions destroying $^{26}$Al (Diehl et. Al. 2006).

In this work we have used $^{26}$Al yields from Limongi and Chieffi (2006). The authors have presented contributions of the wind, the C convective shell, and the explosive Ne/C burning to the total $^{26}$Al yield for solar metallicity stars ranging in mass between 11 and 120 M$_{\odot}$. The $^{26}$Al yield estimates depend on the adopted mass-loss rate, on cross sections, the initial abundances, and the size of the H convective core. Also, the choice of the IMF and assumptions regarding stellar metallicity further affects the $^{26}$Al yields. Thus, the IMF averaged $^{26}$Al yields are the biggest contributor of uncertainty in the $^{26}$Al method.

Average $^{26}$Al yield in the model is a function of the mass of massive stars that explode as core-collapse SNe. Use of an IMF leads to a stellar distribution with fewer high mass stars (that produce relatively more $^{26}$Al) and more lower mass massive stars (that produce less $^{26}$Al). Thus, choice of an IMF affects mass distribution of stars
produced in the model affecting the average $^{26}$Al yield. For example, changing the IMF slope from -2.7 to -2.1 leads to a distribution with a higher number of stars produced in 60-120 $M_\odot$ range compared to 10-60 $M_\odot$ range affecting the total $^{26}$Al produced and thus the average $^{26}$Al yield in the model.
5.6 Summary

In this chapter we studied the $^{26}$Al method in detail and compared results from simulation with observations. In our simulation, the $^{26}$Al contribution from massive star winds is added to the total budget of the $^{26}$Al. We derive a $^{26}$Al line width of $\sim 0.3 \pm 0.15$ KeV from inner Galaxy that corresponds to an average ejecta velocity of $\sim 30$ km s$^{-1}$ which falls within an acceptable range. We also obtain higher flux value in the 4th quadrant compared to the 1st quadrant and a flux ratio of $\sim 1.48$ which is consistent with the observed flux ratio of $1.3 \pm 0.2$ obtained from the SPI data. The blue-shifts obtained from simulation for 4th quadrant are slightly lower than the observed shifts but the theoretical red-shifts are consistent with observations. This irregularity is more likely a result of not including Galaxy’s bar structure in our model. The longitude region between 20° and 40° shows an additional line broadening which is also consistent with observations.

As the results from simulation agree with the observations, we conclude that donut with arms distribution model (free-electron density model of only the thin disk and spiral arms) is a more realistic distribution of the Galactic $^{26}$Al. The addition of the $^{26}$Al contribution from massive star winds provides a better understanding of the $^{26}$Al all sky distribution which is also consistent with the expectations of massive star dominated origin of the $^{26}$Al.

From this work, we conclude:

- In our simulation, massive stars expel $^{26}$Al in wind before exploding as core collapse supernovae and ejecting additional $^{26}$Al. We estimate a SNR of $\sim 1.6$
+ 0.8 events per century. If the $^{26}$Al contribution from massive star winds is excluded from the simulation, we derive a SNR of $\sim 1.9 \pm 0.9$ events per century. Thus, addition of the $^{26}$Al from massive star winds results in a lowering of estimated SNR (and SFR) by $\sim 20\%$.

- We estimate a $^{26}$Al line broadening of $0.4 \pm 0.2$ KeV which could be attributed to modest ejecta velocities and Galactic rotation. Galactic rotation also results in a small $^{26}$Al line shift of 0.2 KeV to the right. This blue shift is consistent with SPI observations. The line broadening of 0.4 KeV corresponds to an average expansion velocity of $\sim 30$ Km s$^{-1}$ which falls within the acceptable range. We also infer that the $^{26}$Al line width remains same for different geometrical models as long as the background model remains same.

- Expanding supernova ejecta leads to a latitudinal broadening of the $^{26}$Al all sky emission. From our simulation, we infer that a latitude spread of $\sim 2^\circ$ could be attributed to the SNe ejecta expansion.

- We estimate a Galactic SFR of $\sim 3.5 \pm 1.7$ M$_{\odot}$ yr$^{-1}$ which is consistent with Diehl et. al (2006).
CHAPTER 6

CONCLUSIONS

In this thesis we have investigated the $^{26}$Al method as a SFR indicator and compared results with other methods. A deeper understanding of Galactic evolution would be incoherent without a well estimated SFR. Stars produce and eject elements in the ISM through stellar winds and supernova explosions. Galactic SNR is related to the Galactic SFR by an IMF. Thus, SFR plays an immense role in shaping the evolution of a Galaxy.

Different methods to measure the Galactic SFR are based on measuring a tracer and connecting it to the SNR and consequently, to the present SFR. These methods include direct attempts like counting historically observed supernova events, and numbering observed SNe in other galaxies and extrapolating this extragalactic SNR to our galaxy. The indirect methods involve studying remnants from associated supernovae and pulsars, and observing gamma-ray lines from radioactive isotopes ejected in supernova explosions and massive star winds.

All methods suffer from varying degrees of selection affects as discussed in chapter 2. For example, the method used by Van den Berg and Tammann (1991) is marred by systematic errors due to incomplete catalogs. Moreover, the actual discoveries are biased against faint SNII and faint parent galaxies at large distances. Similarly, the uncertainty in the ratio of SNe to Pulsars is a major drawback in the Pulsar count method. Likewise, galactic visual extinction and small number statistics influence and affect the outcome from historical supernovae count and SNe remnant methods to a great extent.
The $^{26}$Al method is not affected by extinction. Our galaxy is transparent to $\gamma$-ray line flux and it is possible to view the whole galaxy at once. Sample size is also not an issue in this method. This method is useful, not only to determine Galactic SFR, but it also presents a direct means of tracing the distribution and quantity of sources.

The uncertainties associated with the $^{26}$Al method are largely due to uncertainty in the possible sources of $^{26}$Al and the yields associated with each source. The whole method is also sensitive to the IMF which is related to the SNR and therefore, to the SFR. IMF is also involved in calculating average yields and hence, it is definitely an important source of uncertainty. The assumed spatial distribution models and scale heights also carry their respective uncertainties.

From our study, we can derive few basic conclusions:

- The $^{26}$Al method is not prone to selection affects associated with other methods.
- It is a direct means of deriving the Galactic SFR which is estimated to be $\sim 3.5 \pm 1.7 \, M_\odot \, yr^{-1}$ consistent with Diehl et. Al (2006).
- Addition of the $^{26}$Al contribution from massive star winds results in a lowering of the estimated SNR (and SFR) by $\sim 20\%$.

Recent progress in $^{26}$Al spectroscopy combined with better constrained stellar yields from simulations should further strengthen the $^{26}$Al method as the most direct method to derive global SFR.
APPENDICES
Appendix A

$^{26}$Al observations: A summary

The 1809 keV $\gamma$-ray line emission was first detected with the Ge spectrometer on the HEAO-C spacecraft (Mahoney et al. 1982). This detection was confirmed by the measurement of Galactic transits through the field of view by the NaI spectrometer on the SMM spacecraft [Share et al., 1985]. Compton Gamma Ray Observatory (CGRO) was launched in 1991 to detect light from 20 keV to 30 GeV in Earth’s orbit. The COMPTEL imaging telescope aboard the Compton Observatory performed the first survey of $^{26}$Al $\gamma$-ray line emission in the whole Galaxy. COMPTEL covered the energy range of 1-30 MeV, with an energy resolution of 140 keV (FWHM) around 1809 keV and an angular resolution of 3.8° (Schoenfelder et al. 1993). It was de-orbited in the year 2000 and based on the 9-year COMPTEL observations Plüschke et al. (2001) obtained 1809 keV all sky maps. From the all-sky $^{26}$Al emission image by COMPTEL, the observed 1809 keV $\gamma$-ray line is ascribed to the radioactive decay of $^{26}$Al in the interstellar medium. $^{26}$Al has been found to be predominantly synthesized in massive stars and their subsequent core-collapse supernovae. Furthermore, the $^{26}$Al flux enhancements are directly aligned with regions of recent star formation, such as apparently observed in the Cygnus and Vela regions.
The International $\gamma$-Ray Astrophysics Laboratory (INTEGRAL) is a European (ESA) $\gamma$-ray Observatory Satellite Mission for the study of cosmic $\gamma$-ray sources in the keV to MeV energy range. INTEGRAL was successfully launched on October 17, 2002 using a Proton rocket provided by the Russian Space Agency. Two main instruments on board INTEGRAL are the INTEGRAL imager (IBIS) with an angular resolution of 12', allowing for source localization with arc-min precise with a field of view of $9^\circ \times 9^\circ$ [Ubertini et al., 2003] and the INTEGRAL spectrometer (SPI) with an energy resolution of 2.5 keV at 1.3 MeV and angular resolution of 2.5' within a field of view of $16^\circ \times 16^\circ$. Ge detectors allow for high spectral resolution of 2.5 keV at 1 MeV, suitable for astrophysical studies of individual $\gamma$-ray lines and their shapes. High angular resolution provides a detailed all sky map and high energy resolution helps us to study spectroscopy of gamma ray sources.
Appendix B

Flux comparison tables

Table 1  Donut VS Arms

<table>
<thead>
<tr>
<th>Total events</th>
<th>Flux from Donut ($10^{-4}$ ph s(^{-1}) cm(^{-2}))</th>
<th>Flux from Arms ($10^{-4}$ ph s(^{-1}) cm(^{-2}))</th>
<th>Flux ratio (Arms/Donut)</th>
</tr>
</thead>
<tbody>
<tr>
<td>107036</td>
<td>1.15</td>
<td>1.84</td>
<td>1.6</td>
</tr>
<tr>
<td>100418</td>
<td>1.19</td>
<td>1.80</td>
<td>1.51</td>
</tr>
<tr>
<td>104334</td>
<td>1.04</td>
<td>1.95</td>
<td>1.87</td>
</tr>
</tbody>
</table>

The \(^{26}\text{Al}\) flux emission from Galactic arms is higher than the flux emission from central Donut in our simulation.

Table 5.2  Comparison between Left and right side of the Galaxy

<table>
<thead>
<tr>
<th>Total events</th>
<th>Flux (180(^{0}) to 0(^{0})) ($10^{-4}$ ph s(^{-1}) cm(^{-2}))</th>
<th>Flux (0(^{0}) to -180(^{0})) ($10^{-4}$ ph s(^{-1}) cm(^{-2}))</th>
<th>Flux Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>91300</td>
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</tr>
<tr>
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<td>1.573</td>
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</tr>
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<td>1.523</td>
<td>1.03</td>
</tr>
<tr>
<td>96458</td>
<td>1.51</td>
<td>1.495</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The \(^{26}\text{Al}\) flux emission from negative longitudes is slightly higher that the flux emission from positive longitudes.
BIBLIOGRAPHY


