TRACING GALACTIC STAR FORMATION WITH RADIOACTIVITIES

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ABSTRACT

The galactic star formation rate is a key parameter in the description of the structure and evolution of the interstellar medium (ISM), and further determines the present-day global luminosity of the Milky Way in various bands. Determinations of the star formation rate are based on several distinct tracers: The stellar light component is reprocessed to IR emission by the dust content of the ISM, recombination radiation leads to Hα emission, and particle acceleration in supernova remnant (SNR) shocks leads to a γ-ray continuum. Stellar ejection of radioactive material adds a γ-ray line glow that can be utilized to measure the star formation activity on a galaxy-wide scale. We promote using the 1.809 MeV gamma-ray line due to the decay of ^{26}Al as a powerful technique to measure the global (the Galaxy is transparent to MeV gamma-rays) long-term average (the mean life of ^{26}Al is ~ 1 Myr) star formation rate. This method is compared to standard approaches that rely on scaling the supernova rates in external galaxies to the Milky Way, or the modelling of tracer objects that require significant corrections for evolution, or extinction. We describe the value and limitations of the "^{26}Al-method", which may prove to be one of the most accurate methods once reliable yields are available.

1. SFR/SNR ESTIMATES IN CONTEXT

A survey of the literature demonstrates that measures of the star formation rate and its associated core-collapse supernova rate are currently uncertain by at least a factor two. When one considers these values without taking into account method-specific (i.e. "systematic") uncertainties, one might conclude that we don't know the Galactic SFR to better than an order of magnitude. However, there is some convergence in recent estimates, and we argue that the star formation- and the related supernova rates are now established to within less than a factor 2. Still, further improvements in the measurement of this important quantity are possible.

We are concerned about systematic effects in methods using indirect scaling to rates of external galaxies, or extrapolation from a very local star formation tracer to a global model. We advocate an approach based on γ-ray line measurements; these are well suited for a galaxy-wide estimate, as the MeV band does not suffer from extinction, and yield a time average on scales that are long in comparison to the typical times between events, thus minimizing the effects of small number statistics. Before presenting the key features of this "^{26}Al-method", and the recent results obtained from its application to INTEGRAL data, we will briefly review some of the methods that have been used in the past (as summarized in the table).

Generically, the star formation rate (SFR, expressed in solar masses per year, $M_{\odot}\ y^{-1}$) is obtained from a tracer that can be corrected for observational selection effects and is understood well enough so that evolutionary effects can be taken into account. One either deals with a class of residual objects, such as pulsars or supernova remnants, or with reprocessed light, such as free-free, Hα, or IR emission that follows from ionization and heating of interstellar gas and its dust content in the vicinity of hot and luminous stars. In some cases one should include time-dependent effects, because the observational phenomena are caused by processes which include their own characteristic evolution with time. The "after-glow" of an instantaneous starburst behaves differently than the steady state output from a region with continuous star formation. Here we are concerned with an average (steady state) star formation rate, where "average" is to be understood as spatial (galaxy-wide) and temporal, over long enough time scales to avoid distortion from fluctuations and not too long for galactic evolution to matter (i.e., $<10^8$ y, which would be a typical time for morphological changes in the Galaxy itself).

To give a sense of how the measurements of the SFR have evolved over time, we present a Table of values that were drawn from the literature over nearly the past three decades. This selected set of citations is not meant to be complete, but a representative sample. A graphic rendering of this table is presented at the end of this paper.

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Authors	SFR (M_o/yr)	SNR (century $^{-1}$)
Smith et al. 1978	5.3	2.7
Talbot 1980	0.8	0.41
Guesten et al. 1982	13.0	6.6
Turner 1984	3.0	1.53
Mezger 1987	5.1	2.6
McKee 1989	3.6 (R) 2.4 (IR)	1.84 1.22
van den Bergh 1990	2.9	1.5 +/- 0.8
Van den Bergh & Tammann 1991	7.8	4
Supernova Remants	6.5 +/- 3.9	3.3 +/- 2.0
Historic SN Record	11.4 +/- 4.7	5.8 +/- 2.4
Cappellaro et al. 1993	2.7 +/- 1.7	1.4 +/- 0.9
Van den Bergh & McClure 1994	4.9 +/- 1.7	2.5 +/- 0.9
Pagel 1994	6.0	3.1
McKee & Williams 1997	4.0	2.0
Timmes, et al. 1997	5.1 +/- 4	2.6 +/- 2.0
Reed 2005	2-4	1-2
Diehl et al. 2005	3.8 +/- 2.2	1.9 +/- 1.1

We briefly discuss some of the methods used to estimate the galaxy-wide star formation rate. Related quantities of interest, such as the production rate of stars (in units of stars per year) or the type-II (and Ibc) core-collapse supernova rate (in units of events per century) are provided, if given in the original paper. If only the supernova rate (SNR) or the star formation rate (SFR) is given, we convert one quantity to the other by using the specific initial mass function (IMF) "calibration" used by McKee and Williams [12]: SFR = 1.96 SNR, in units defined above.

Supernovae only trace stars from the upper IMF, thus statements about the SFR (including all stars) are sensitive to the full mass range of the IMF employed. On the other had, some quantities, such a supernova yields and ionizing fluxes, are only sensitive to assumptions about the IMF above about 10 $M_\odot$. To enable a direct comparison of published results we normalize to [12]. Uncertainties in each quantity should be treated separately, as methods that directly determine the SNR yield a less accurate SFR due to the added uncertainties for the low mass IMF.

Many papers discuss the Star Formation (rate) History (SFH) in relative terms (studies not concerned with the absolute value of the SFR, but with the relative history of the rate), or the star formation rate surface density ($M_\odot$ y^{-1} kpc^{-2}) in the solar neighborhood, and possibly its radial dependence. Papers are not listed if the global SFR was not explicitly addressed or is only derivable with model assumptions not provided in the original work.

Our first reference is to Smith, Biermann, and Mezger [1], who studied HII regions and estimated the number of Lyman continuum photons required to maintain the ionization of these regions. They find SFR = 5.3 M_o/yr.

Following the footsteps of [1] Talbot [2] investigated the rate of star formation with observed intensities of CO and HI emission in the Milky Way (and M83) and finds SFR = 0.8 M_o/yr.

Güsten and Metzger's [3] estimate of the total ionizing luminosity obtained from observations of HII regions implies a SFR of 13.0 M_o/yr, of which they attribute (5 +/- 4) $M_\odot$ /yr to spiral arm activity.

Turner [4] reviews the observational data pertaining to regions of star formation, in particular in radio bands, and advocates SFR = 3.0 M_o/yr.

Mezger [5] constrains SFR estimates from the Lyman continuum photon production rate with estimates of the mass distribution of the galactic disk, and finds a SFR of 5.1 M_o/yr.

With a model for the rate of low-mass star formation in molecular clouds McKee [6] finds a SFR of 3.6 $M_\odot$ /yr from the analysis of thermal radio emission from HII regions, which is proportional to the production rate of ionizing photons, which in turn is proportional to the SFR. It is pointed out that this method is sensitive to the slope of the high-mass IMF. It also must be noted that the method depends on stellar atmosphere models in conjunction with models for massive stars, which change with treatments of mass loss, rotation, and convection. This paper also briefly discusses the use of the far-IR luminosity, due to warm dust heated by the absorption of photons from massive stars. The author uses the measured IR luminosity of the Galaxy of 4.7 10^9 L_o (from [5]) to derive a SFR of 2.4 M_o/yr.

At this point we introduce the first reference to work in which the primary focus was a direct estimate of the supernovae rate (in our context we are only interested in the core-collapse rate (Types II, and Ibc) . Van den Bergh [7] finds (2.62 +/- 0.8) h_{100}^2 century^{-1}. For h_{100} = 0.75, the rate is 1.5 +/- 0.8 century^{-1}. This rate is based on a combined study of Galactic supernova remnants, the small set of historical SNe, and supernovae in M31 and M33. Cappellaro et al. [9] later refer to this rate as "the best estimate"

Van den Bergh and Tammann [8] find a SNR of ~4 per century. The authors review supernova rates in external galaxies and derive a specific supernova frequency, in units of 1 SNu = 1 SN per century per 10^{10} $L_\odot$(B), for various galaxy types. If one assumes that the Galaxy is intermediate between types Sab-Sb and types Sbc-Sd, the specific rate is ~3 h_{100}^2 SNu. For a Galactic blue-band luminosity of L(B) = 2.3 10^{10} Lo(B) (their Table 11) and h_{100} = 0.75 we infer a SNR of 4 per century. They also discusses estimates from internal Galactic tracers: from radio supernova remnant (SNR) statistics they infer a SNR of 3.3 +/- 2.0 century^{-1}. The historic record of nearby (< a few kpc) supernovae in the past millennium they (Tammann) argue for a SNR of 5.8 +/- 2.4 century^{-1}. Large extinction corrections in the galactic plane render this sample highly incomplete, which results in very large uncertainties when one extrapolates to the full galactic disk. The authors also review efforts based on the pulsar birth rate, but their extensive observational selection effects together with strong (and poorly understood) evolution of luminosity and beaming renders this method impractical for estimating the galactic SNR.

Along these lines of studies, Cappellaro et al. [9] find a SNR of 1.4 +/- 0.9 century^{-1} based on scaling the rate in the Galaxy to that in external galaxies of similar type. Their sample is obtained from surveys carried out at the Asiago and Sternberg Observatories. The authors provide an extensive discussion of the uncertainties of this method, which can exceed 200% for some late type galaxies.

Subsequently, van den Bergh and McClure [10] find a SNR of 2.4-2.7 h_{75}^2 century^{-1}, after re-evaluating extra-galactic SN rates obtained from Evans's 1980-1988 observations. This result relies on extrapolation from other galaxies, and thus a proper evaluation of the type and B-band luminosity of the Galaxy. The uncertainty due to the Hubble constant is now very small. Given the error analysis in the paper, the rate is uncertain by at least 34%. We enter 2.5 +/- 0.9 century^{-1} in the table.

In Pagel's [11] textbook on galactic chemical evolution we find a SFR of 6.0 $M_\odot$ /yr.

McKee and Williams [12] study the galactic luminosity distribution of giant OB associations, and infer a SFR of 4.0 $M_\odot$ y^{-1}, and based on the Scalo-IMF convert this rate into a total number rate of 7.9 stars per year. They assume that all stars above 8 M_o become supernovae, corresponding to a supernova fraction of f_{SN} = 2.6 10^{-3}. With a mean stellar mass of <m> = 0.51 $M_\odot$, the corresponding cc-supernova rate is thus 2 per century. As mentioned above, we use this study for calibration

$$SFR(M_\odot y^{-1}) = \langle m \rangle f_{SN}^{-1}\ SNR = 1.96\ SNR(century^{-1}). \quad (1)$$

Timmes, Diehl, and Hartmann [13] applied the "^{26}Al-method", described in the next section, to the data from COMPTEL and obtain a SFR of 5.1 +/- 4 $M_\odot$/yr. For the steady state equilibrium mass of ^{26}Al in the present-day ISM they obtained a range 0.7 – 2.8 $M_\odot$, based on the Salpeter IMF (0.1 $M_\odot$ - 40 $M_\odot$) and ^{26}Al yields from Woosley and Weaver [15] [which do not include the contributions from Wolf-Rayet winds]. Their SFR implies a cc-supernova rate of 2.6 +/- 2 century^{-1}. The neglect of hydrostatically produced ^{26}Al injected into the ISM by winds from massive stars, caused their SFR to be overestimated. The large uncertainty in the final result for the SFR is due to large uncertainties in the observed COMPTEL flux. Recent INTEGRAL observations have significantly reduced the error in this key quantity and also provided support for the basic idea that ^{26}Al is indeed distributed globally in the ISM. Diehl et al. [14] use INTEGRAL measurements to obtain a SNR of 1.9 ± 1.1 century^{-1}, corresponding to a SFR of 3.8 ± 2.2 $M_\odot$ y^{-1}, as discussed below.

Recently, Reed [16] estimate the birthrate of stars with masses in excess of 10 $M_\odot$ using a sample of local OB stars. He does not state a value for the SFR, but states "… the galactic supernova rate is estimated as probably not less than 1 nor more than 2 per century". Using the conversion factors from [12] one thus infers a SFR in the range 2-4 $M_\odot$ y^{-1}. Reed uses a sample of about 400 O3-B2 dwarfs within a heliocentric distance of 1.5 kpc, and then extrapolates based on models for the spatial distribution of stars, galactic extinction, and stellar life times. Reed emphasizes various sources of errors, such as lacking spectral classifications of some bright OB stars, the (unknown) inhomogeneous spatial structure of extinction as well as stellar density, and non-unique connection between mass and spectral type, and draws attention to the fact that one would have to include B3 dwarfs as well, if the lower mass limit for supernovae is 8 $M_\odot$ instead of 10 $M_\odot$ (e.g., [17]). The OB-star catalog of the author was used to perform a modified V/Vmax test to obtain a present-day star count as a function of absolute V-band magnitude. From the stellar life times and the assumption of steady state the local birthrate follows. A double exponential model (in galactocentric radius and scale height above the plane) of the spatial distribution of these stars (which includes an inner “hole” of radius R = 4.25 kpc) ultimately leads to a total birthrate of about one OB stars per century. Variations in the size of the hole change this number significantly, which leads the author to finally derive a rate of 1-2 supernovae per century. Extrapolating star counts in the solar vicinity to the global count clearly is sensitive to the spiral model one uses for the non-symmetric part of the galactic star formation pattern. Molgaard, Hartmann, and Diehl [18] carried out Monte Carlo simulations to address this issue, and find that pulsar-based distribution models from [19,20] imply an additional uncertainty of at least a factor of two. With future astrometry missions such as GAIA we should significantly improve the understanding of the global distribution of stars in the Galaxy, and thus reduce this source of uncertainty. Presently we should regard star-count measurements of the SFR as rather uncertain.

Figure 1 shows the SFR values discussed above (and a few more we did not describe in detail), demonstrating that, with few exceptions, the SFR estimate converged to a range of 2-4 $M_\odot y^{-1}$. From eq. (1) we thus infer that the galactic core collapse rate should be in the range of 1-2 per century, a value that is now commonly used. The pulsar-historic-SN-based estimate in the recent textbook *Astrophysics* (Kundt 2004, Springer Verlag) is significantly higher than this advocated value, but, as pointed out above, uncertainties due to assumptions about extinction, pulsar beaming and lifetime are large.

2. RESULTS FROM THE ^{26}AL METHOD

Using γ-rays from radioactive ^{26}Al ejected galaxy-wide by massive stars, we established an alternative method [13,14] to obtain a global measure of the galactic SNR (and thus the SFR). This is made possible because ^{26}Al gamma-ray line emission is observable throughout the Galaxy, and the decay of ^{26}Al occurs in the interstellar medium on a characteristic time scale long compared to that of ^{26}Al ejection events and the dynamics of individual stellar explosions, sampling over 10,000 such events. A key advantage of the “^{26}Al method” is the fact that our Milky Way is basically transparent to 1.8 MeV photons from the decay of this isotope, and that the yields are now reasonably well known [21]. Production of ^{26}Al in ccSNe is abundant (about 10^{-4} M_o on average), so that the approximately 10,000 events per mean life of ~10^6 yrs accumulate a steady-state average amount of a few solar masses in the ISM. The diffuse γ-ray line glow from this smoothly distributed trace element results in a total flux of

$$F_{1.8} \sim 1.510^{-4} M_{26} D^{-2} (\gamma / cm^2 s), \quad (2)$$

where D is an effective distance, normalized to an assumed distance R_{GC} = 8.5 kpc to the Galactic Center. The value of D is dependent on the assumed overall scale of the galaxy and the relative distribution of ^{26}Al sources (traced by a combination of massive, young stars and an older nova population). The steady state mass of ^{26}Al (in solar masses, $M_\odot$)

$$M_{26} = \langle Y \rangle \cdot R_{SN} \cdot \tau = 1.410^{-4} M_0 \cdot R_{SN} \cdot \tau \quad (3)$$

is given by the product of mean yield, <Y>, the ccSN rate R_{SN} (which we wish to obtain), and the mean life $\tau(^{26}Al)$ = 1.03 10^6 yrs, which is well established and thus does not contribute much to the error budget. The largest source of uncertainty is due to <Y>, which has two contributing sources, the IMF for masses above m_{SN} ~ 8-10 $M_\odot$, and the model-dependent yields as a function of progenitor mass, m. For the purpose of this study one must combine ^{26}Al mass (yields) ejected in the Wolf-Rayet wind phase prior to the supernova and the explosive yield. Diehl et al. [14] compiled the theoretical $Y_{26}(m)$ predictions from several groups, and derived the high-mass IMF-averaged yield used in eq. 3. With this value of <Y>, the INTEGRAL flux in the 1.809 MeV γ-ray line from the inner Galaxy implies (from eq. 2) a SNR of 2 ± 1 ccSNe century^{-1}, and a SFR of 4 ± 2 $M_\odot$ y^{-1}. Eq. 3 then implies that the diffuse glow of the Milky Way in the 1.809 MeV γ-ray line stems from the decay of about 3 $M_\odot$ of ^{26}Al.

3. THE ^{60}Fe AND ^{44}Ti METHODS

A similar method for estimating the star formation rate of the Milky Way can be based on other γ-ray line tracers, as long as the yields are large enough to allow detection. Isotopes with long decay times, compared to the time between source events, result in a diffuse glow of the galactic plane from a large number of sources that contribute in a few mean decay times (~10,000 in the case of ^{26}Al). In case of a short decay time, one deals with a small number of sources, which must be detectable individually. The former category includes gamma-ray lines from the isotope ^{60}Fe, which is co-produced with ^{26}Al in ccSNe with similar yields [15, 21, 22], and the latter category includes ^{44}Ti, which has yields similar to ^{26}Al and ^{60}Fe, but a short decay time of τ ~ 85 yrs, so that γ-ray surveys have only been able to establish one source with high significance, Cas A [23, 24].

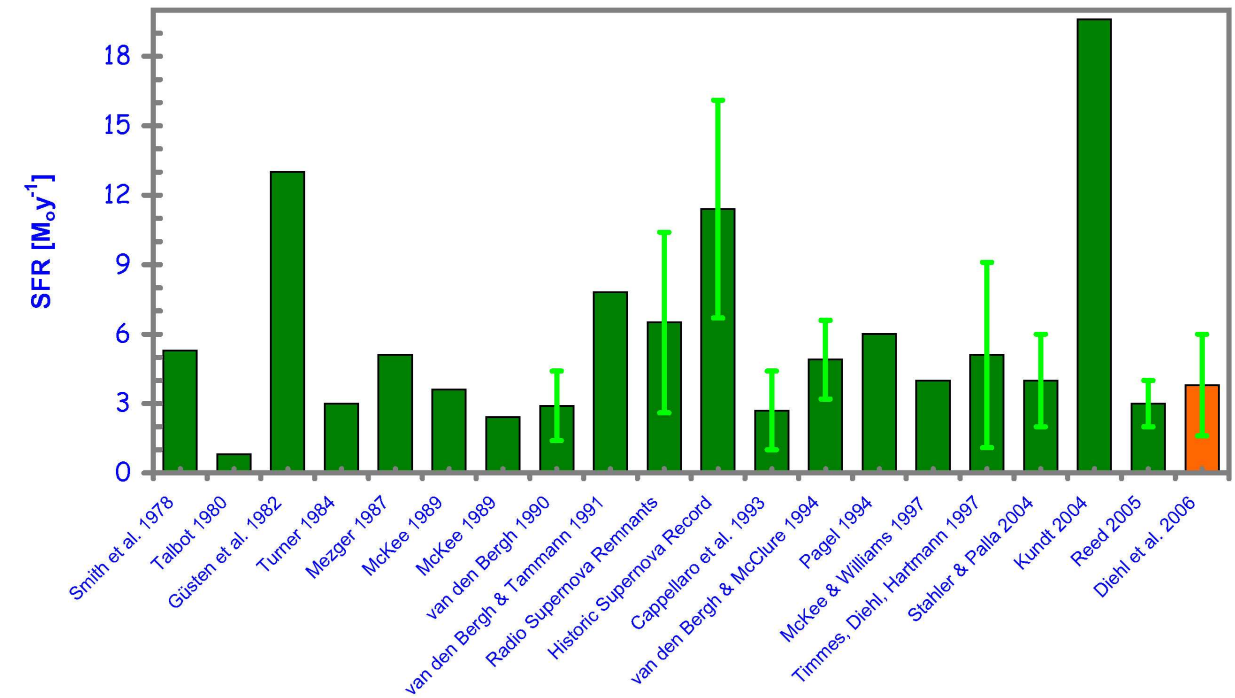

Fig. 1: A comparison of the star formation rate estimates presented in Table 1 and discussed in the text. Our estimate based on ^{26}Al radioactivity gamma-rays is consistent with results from alternative, albeit more indirect methods. Once nucleosynthetic yields of massive stars are better constrained, this could be one of the more precise approaches to determine the star formation rate throughout our own Galaxy.

The discovery with COMPTEL [23] of the 1.157 MeV γ-ray line from ^{44}Ca in the decay chain ^{44}Ti → ^{44}Sc → ^{44}Ca from the young (~ 335 years) and relatively far (3.4 kpc) SNR Cas A suggested that deeper surveys would yield further detections from other supernova remnants. Despite initially promising candidates, this expectation has not yet been fulfilled [25], and The et al. [26] interpret the surprising absence of additional γ-ray detectable supernovae from the past three centuries as an indication that either core collapse supernovae have been improbably rare in recent times, or that ^{44}Ti-producing supernovae are atypical events. Resolving this question with still deeper γ-ray surveys will require a next generation instrument with at least one order of magnitude improvement in the flux limits [26].

A spatially resolved flux map like the one for ^{26}Al does not yet exist for ^{60}Fe. However, the presence of ^{60}Fe in the ISM has now been detected with RHESSI [27-29] and also SPI/INTEGRAL [30]. The flux ratio of their respective lines, F_{60}/F_{26} = F(1.17 or 1.33 MeV)/F(1.809 MeV), is in the range 01.-0.3 [31], and thus consistent with the predicted value of 0.15 [13]. However, the interpretation of this flux ratio is hampered by large uncertainties in the yields [21, 32] (mostly from stellar model assumptions about mass loss, rather than the uncertainties in the nuclear physics). Progress on this frontier will require a ^{60}Fe map with a quality similar to the one accomplished for ^{26}Al, rather than just the flux ratio. The detection of the longer-lived ^{60}Fe isotope is opening the door to comparative studies in which the dynamic evolution of the radioactivities in the ISM can be studied.

4. CONCLUSIONS

We used the observed galactic 1.8 MeV flux measured by INTEGRAL to estimate the Galactic production rate of this isotope, and thereby inferred the average, global star formation rate. We found that about 4 ± 2 $\mathbf{M_\odot}$ of gas is converted to stars each year. This value assumes the IMF used in [12], corresponding to the conversion SFR = 1.96 SNR. The supernova rate SNR = 1.9 ± 1.1 events per century is the primary result of the ^{26}Al-method, and follows from the total 1.8 MeV flux in conjunction with distribution models for massive stars and isotopic yields provided by theoretical studies of hydrostatic and explosive nuclear burning in pre-supernova stars and their subsequent explosions. Here we used the IMF-averaged yield that discussed in [14]. The "^{26}Al-method" offers a unique and powerful way for measuring the global Galactic star formation rate, a quantity that plays a key role in Galactic astrophysics.

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