ABUNDANCES IN THE GALACTIC CENTER

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ABSTRACT

Abundance measurements in the Galactic Center (GC) probe material with a nucleosynthetic history unique in our Galaxy. The measurements are of two types: probing interstellar and stellar material. Measurements of gas-phase abundances are mostly toward SgrB2 and SgrA. They reflect the current state of nuclear evolution in the GC and include several important isotope abundance ratios. The isotope ratios provide the most accurate information and allow for comparison with results elsewhere in the interstellar medium. The second type of measurement is of abundances in (and around) stars, yielding chemical abundances in the bulge and disc populations, and reflecting the state of nuclear evolution when the stars were born.

When combined with our knowledge of evolution in the solar neighborhood, several of the results are consistent with the the greater nuclear "maturity" of the inner Galaxy. However, there are several important exceptions, which point to the fact that we really do not understand nuclear processing in the GC region. Some of the open issues may be resolved observationally, and with new infrared and millimeterwave techniques a clear opportunity exists to improve the observational record. Results should increase our understanding of stellar nucleosynthesis and of the history of star formation in the GC.

1. INTRODUCTION

The GC has a cycle of stellar birth and death which is quantitatively different from that of other regions, underscoring the need for a useful set of models as well as for new observational material. The GC contains the most massive interstellar clouds in the Galaxy, yet it has a very low gas fraction (Audouze et al., 1975; Güsten and Ungerechts, 1985). The incidences of supernovae and planetary nebulae (PN), relative to the Solar neighborhood, are small when contrasted to the total mass (the astration rate/stellar mass = 3×10^{-11}/yr), but they are large compared to the gas mass. Since the efficiency of star formation is evidently large relative to that in the solar neighborhood, the present-day GC abundances are often thought to presage the evolution of the Galaxy as a whole. On the other hand, the highly enriched and turbulent gas in the GC may produce a stellar

M. Morris (ed.), The Center of the Galaxy, 107–119.

population (initial mass function) which will never be seen in the less active regions of the outer Galaxy.

Table 1: Comparison of Galactic Center vs. Solar Neighborhood

	Galactic Center	Solar Neighborhood
gas/star mass ratio	$(2 - 10)\ 10^{-4}$	$(1 - 1.5)\ 10^{-1}$
rate of supernovae explosions		
- per unit total mass	$(2 - 15)\ 10^{-14}\ yr^{-1}\ M_{O}^{-1}$	$(2 - 8)\ 10^{-13}\ yr^{-1}\ M_{O}^{-1}$
- per unit mass of gas	$(0.2 - 8)\ 10^{-10}\ yr^{-1}\ M_{O}^{-1}$	$(1.3 - 8)\ 10^{-12}\ yr^{-1}\ M_{O}^{-1}$
rate of formation of planetary nebulae		
- per unit total mass	$(0.7 - 6)\ 10^{-11}\ yr^{-1}\ M_{O}^{-1}$	$(0.5 - 2)\ 10^{-11}\ yr^{-1}\ M_{O}^{-1}$
- per unit mass of gas	$(0.7 - 30)\ 10^{-8}\ yr^{-1}\ M_{O}^{-1}$	$(0.3 - 2)\ 10^{-10}\ yr^{-1}\ M_{O}^{-1}$

(from Audouze, Lequeux and Vigroux, 1975) Comparison of properties of the galactic center (inside ~200 pc) and the solar neighborhood. Supernova explosions monitor the rate of formation and death of massive stars ($\gtrsim 5M_{O}$), planetary nebulae monitor the death rate of less massive stars ($\lesssim 5M_{O}$).

Some indirect evidence about gas-phase abundances in the nuclear bulge can be obtained from observations of HII regions in external galaxies, but these cannot yield the detail, in terms of the number of nuclides, which is available in our own GC to infrared and radio astronomers.

Models of nuclear evolution provide the means for comparing abundances of different nuclides, including the isotopes of given elements. The accumulated literature about nuclear evolution is extensive but can, for the present purposes, be summarized by grouping the nuclides by the order in which they are produced by stars. An initial complement of H, D and He produce primary nuclides such as ^{12}C and ^{16}O in normal and low-metal stars. These primary nuclides, may subsequently produce or catalyze the production of secondary (and tertiary) nuclides, such as ^{14}N and ^{13}C. If the production within stars proceeds in concentric shells without radial mixing, then the secondary elements must be produced in subsequent generations of stars. However, recent theoretical and observational evidence has blurred the distinction between the primary and secondary elements in two ways: 1) stars with deep mixing in their late life can produce "secondary" nuclides within a single generation and 2) the relatively short lifetimes of massive, low-metal stars can minimize the apparent, steady evolution from primary to secondary nuclides. Nontheless, as we shall see, the distinction between primary and secondary nuclides remains a useful concept, if only in a statistical sense.

2. THE EVOLUTION OF NUCLEAR ABUNDANCES

The products of hydrogen and helium burning are of greatest interest in order to follow the history of star formation in the GC. These products are the isotopes H, He, C, N, O and some Ne. The heavier elements, such as Si, Mg, S, and the iron-peak nuclides, are by and large produced and expelled exclusively from supernovae, so that details of their abundances reflect more upon the nature of the supernovae themselves than upon the general history of stellar production.

The expected situation for nuclear processing in the GC is that which would apply to any metal-rich region: that there should be an increase in the primary/primordial abundances (He/H, $^{12}C/H$, $^{16}O/H$, etc), and in the secondary/primary ratios ($^{14}N/^{16}O$, $^{13}C/^{12}C$, $^{17}O/^{16}O$). The D/H ratio should decrease due to the easy burning of D to form He and certain other ratios such as $^{17}O/^{18}O$ and $^{15}N/^{14}N$ depend on details of stellar production.

Are there other ways to verify our expectations than to compare the GC to the galactic disc? Certainly, for low-metallicity regions, there is no lack of evidence concerning the elemental abundances, gathered from the Magellanic clouds and from other galaxies. However, the extrapolation to metal-rich gas is more difficult to verify. A very useful input is to consider directly the nuclear abundances in evolved stars and stellar remnants, being the actual engines of nuclear enrichment for the interstellar medium. One useful data point, especially for the CNO isotopes, is to look at late-type stars which eject the products of CNO cycling. Supernova remnants are also very interesting, but the available observations are sparse and are not yet applicable to the GC. In contrast to the more evolved abundances of the GC and the stellar remnants, the local interstellar medium provides a reference point for the current state of evolution and the Sun (and Earth) is usually taken to represent a fair sampling of the more metal-poor material as it existed locally 5 billion years ago.

Thus, there is a sequence of "nuclear age" in which to evaluate GC abundance data: 0) primordial abundances 1) Magellanic Clouds, metal-poor galaxies, 2) the Sun, 3) the local (and not-so-local) interstellar medium, 4) the GC (?) and, 5) mass-loss stars and stellar remnants. For each nuclear abundance ratio, we can find out if 1) there is an obvious evolution with increasing exposure and 2) if the GC fits as expected into the sequence.

3. THE GALACTIC CENTER AS A NUCLEAR ENTITY

The term "Galactic Center" means different things to different astronomers, having scales from 1 pc to 1 kpc. The available abundance data are derived from radio, infrared and optical observations of the interstellar gas, giant stars and PN. The astronomical objects have different locations and histories within the GC. Ultimately, these differences should provide interesting details about the history of the GC. For the moment however, the observational record very patchy and we will look only for common trends.

3.1 The Gas: (r < 300 pc)

Interstellar isotope ratios and limited element abundance data are available for several objects within the inner disc of the GC, mostly from radio/millimeterwave observations. Many of the observations are of gas associated with SgrA and SgrB2, but there have also been observations of an interconnecting molecular ridge and SgrC. The observed gas is assumed to lie within 300 pc of the GC but outside of ~100 pc; the tidal limit set by the central stellar distribution. Related to the SgrA sources is a continuum "crescent" or "arc", providing background illumination for radio lines. One concept of the relative location of these objects is given by Güsten and Downes, 1980 (Figure 1).

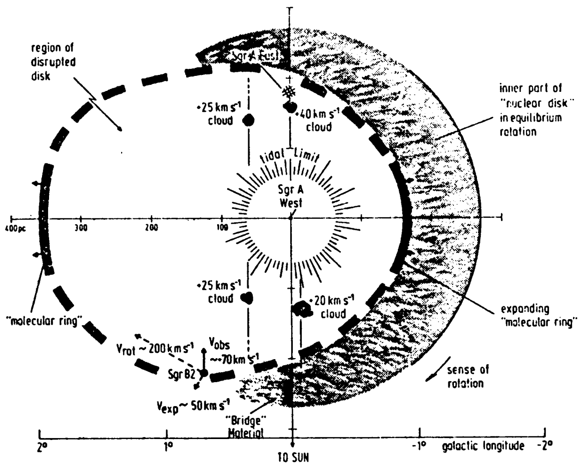

Figure 1. Possible locations of molecular clouds in the galactic center region, as viewed from above the galactic plane. The shaded crescent represents the inner part of the nuclear disk. The dashed oval is the suggested location of the expanding molecular ring. Vertical lines indicate uncertainty in cloud locations along the line of sight.

For purposes of interpreting the abundances of the GC, it is sufficient to accept that the interstellar material listed represents a common nuclear exposure as a result of interstellar mixing and/or of a common history of stellar processing. Indeed, the available data indicate uniformity: maps yielding constant ratios within clouds (c.f., Beiging et al., 1980; Lis and Goldsmith, 1989) and observations of several positions and velocities within the GC likewise showing no significant differences among the GC sources.

3.2 Stars in the bulge: (r < 500 pc)

Certain element abundance ratios can be determined from giant stars, especially in favored directions of low obscuration known as "windows". Baade's window is one such direction, but there are others as well. Stellar velocities are used to indicate kinematic membership to the bulge population. Observations of bulge stars have the further advantage that they allow for direct comparisons with observations of the nuclear regions of other galaxies. Of course, the stellar material represents an earlier epoch of nuclear evolution than the gas, but the observed stars are younger than the Sun on the average so that the age difference is probably not significant for the existing data set.

3.3 Planetary Nebulae: ($r < 1000$ pc)

PN can yield high-quality element abundance data, but the number of objects is more limited than for the giant bulge stars. PN are observed at galactocentric distances between 0.5 and 1.0 kpc, and it is a valid worry that they are not representative of GC abundances. Nontheless, they should still represent a probe of material more heavily processed than that in the solar neighborhood.

4. NUCLEOSYNTHESIS OF THE H, He, C, N AND O NUCLIDES

There are seven stable CNO nuclides, and four stable H and He nuclides uniquely identified by their nuclear weights, which range from 1 to 4 and 12 to 18. Each of these nuclides is produced (destroyed) in its own particular niche of stellar nucleosynthesis and any or all of the possible abundance ratios can be used to illuminate some aspect of the history of nuclear production.

Of the three possible ratios of the stable H and He nuclides, the D/H ratio is probably the most sensitive to stellar nucleosynthesis (c.f., Epstein, 1977). The primordial complement of D, resulting from the big bang is effectively destroyed in the envelopes of all stars. Therefore D/H provides a direct measure of the remaining primordial material. The He/H ratio provides a measure of total stellar nucleosynthesis, indicating the fraction of H burned. However, the usefulness of He/H is limited by the large primordial complement of He, which can mask the fractional enhancement by stellar production except where the ratio can be very accurately measured. The processing of ^{3}He is more complex: the primordial complement probably destroyed in massive stars and enhanced in low-mass stars (Rood, Steigman and Tinsley, 1976; Dearborn, Schramm and Steigman, 1986). Therefore, its abundance in the GC should only be interpreted in light of other observations which indicate evolutionary trends.

Next, in terms of stellar production, are the seven CNO nuclides. Each can be characterized by its place in the sequential production: primary if it can be produced directly from H and He, and secondary (or higher) if production requires the prior synthesis of other CNO nuclides.

^{12}C and ^{16}O are the only two of the CNO nuclides clearly identified as primary in nature. They are products of helium burning, ^{12}C by operation of the 3-α reaction and ^{16}O by a subsequent addition of helium. Both are produced (and ejected by) massive stars (MS's). In addition ^{12}C can also be dredged up and ejected by intermediate-mass stars (IMS's).

^{13}C, ^{14}N, ^{15}N, ^{17}O and ^{18}O are secondary products of nucleosynthesis, using ^{12}C,

^{14}N and/or ^{16}O as seed nuclei. However they may behave like primary products in terms of galactic production, due to deep mixing within IMS's (c.f., Iben and Truran, 1978) or, in the case of ^{15}N, by mass transfer (see additional discussion below). ^{13}C, ^{14}N, ^{15}N, and ^{17}O are the products of hydrogen burning, ^{14}N being the major product of the cold ($T < 10^8$K) equilibrium CNO cycle in main sequence stars and red giants. ^{14}N is expelled from IMS's in dense winds. ^{13}C and ^{17}O are produced by incomplete CNO burning: the addition of H to an initial mix containing ^{12}C and ^{16}O. Equilibrium CNO burning does enrich ^{13}C and ^{17}O relative to ^{12}C and ^{16}O, but so little oxygen and carbon are formed altogether that the large interstellar pool of CNO nuclides is not significantly affected. ^{15}N is most efficiently produced in hot CNO burning, where the slowest reaction is the beta-decay of ^{15}O. Also, like ^{13}C and ^{17}O, it can be produced in explosive (incomplete) burning in novae (IMS's) or supernovae (MS's). ^{18}O (like ^{16}O and ^{12}C) is produced by He burning, but on a seed of ^{14}N, making it a secondary nuclide.

5. THE ABUNDANCE DATA

5.1 abundances in the gas: isotopic ratios

The four stable nuclides of H and He yield three ratios, observable in the gas phase by radio and IR observations. These light nuclei are important to observe, but the data, especially in the GC need improvement. Abundance ratios among the seven CNO nuclides provide more detail and provide ample evidence for systematic evolution (Table 2).

TABLE 2: CNO Abundances Relative to Solar Values

Material	$^{17}O/^{18}O$	$^{13}C/^{12}C$	$^{17}O/^{16}O$	$^{18}O/^{16}O$	$^{14}N/^{15}N$
Solar Value	1/5.5	1/89	1/2630	1/490	1/273
Solar	1.0	1.0	1.0	1.0	1.0
Outer Galaxy	1.48±0.05	1.4±0.3	1.1±0.3	1.0±0.2	1.1±0.15
Galactic Center	1.59±0.10	3.2±0.8	2.9±1.2	2.0±0.8	2.5±0.6
Red Giants[a]	9(2.2-16)	6(1-16)	6(2.4-16)	0.9±0.3	(2-10)

[a]From Wannier, 1985

5.1.1 D/H

Deuterium observations have been made using various techniques, ranging from the 92 cm radio line to ultraviolet observations (c.f., Blitz and Heiles, 1987; Vidal-Madjar et al., 1986; Penzias, 1979). Most of the effort has gone into the local interstellar medium, to establish the primordial value and thereby, the baryon density of the early universe. In terms of galactic nucleosynthesis, the most useful observations are those using the millimeterwave transitions of deuterium-substituted molecules, including several species observed in the GC. Although chemical fractionation is certain to play a large role, it has been argued that radial gradients may nontheless indicate the relative amounts of un-astrated material (Penzias, 1979). Such a gradient is indicated on the basis of observations of HCN, HCO^+ and NH_3, in the sense of depletion (factor 2-5) in the GC, consistent with its more extensive nuclear processing (Wannier, 1980).

5.1.2 He/H

Available observations of He in the GC come from radio recombination lines (c.f., Pauls and Mezger, 1980) and infrared observations of HeI (Geballe et al., 1984). Although the radio recombination line toward SgrA yields He/H < 0.03, the effects of fractional ionization are difficult to determine. Observations of recombination lines toward SgrB2 range from <0.02 to 0.085±0.015 based on simple interpretation, but Pitault and Cesarsky (1980) conclude that when suitable corrections are made for the effects of source models on the line intensity ratios, the existing values are all consistent with H/He=0.1 which is the general cosmic value. The same conclusion applies to the broad infrared lines seen in the direction of IRS16 by Geballe et al., (1984) who conclude that in the high-velocity outflow He/H is near its solar value. Thus, there is no conclusive evidence for an increase in He toward the GC.

5.1.3 ^{3}He/H

The 8.7 GHz hyperfine line of ^{3}He has been used to measure the He/H ratio in nine galactic HII regions varying in galactocentric distance from 0.1 to 19 kpc (Bania, Rood and Wilson, 1987). Although there is evidence for source-to-source variability, there is no evidence for a galactic gradient. ^{3}He appears to be enhanced (factor 2 to 4) in the GC (SgrB2), but the large spectral line widths make this result uncertain. More recent observations in galactic HII regions may also indicate time variability in at least one galactic source (Heiligman, 1988). Overall, the present data are inconclusive.

5.1.4 ^{12}C/^{13}C

^{12}C/^{13}C is the most frequently measured isotope ratio. In the GC, it has been determined from observations of at least nine different molecules: CO, CS, OCS, HCO^+, H_2CO, C_3H_2, CH_3OH, HC_3N and NH_2CHO. This wealth of data not only provides for consistency checks, but also provides a measure of possible isotope fractionation effects. Most of the observations are toward SgrB2 and SgrA (west), but there are also scattered observations toward other molecular clouds of the inner disc (Wannier, 1980 and ref.'s therein; Henkel et al., 1983; Gomez-Gonzalez et al., 1986; Kuiper et al., 1988)

Given the wide diversity of techniques, the results are surprisingly consistent, with ^{12}C/^{13}C ranging from about 20 to 40, and generally consistent with a single value of 28.

$^{12}C/^{13}C$ observations are affected, to some extent, by fractionation reactions which selectively shunt ^{13}C to one or another molecular species. Nontheless, accurate determinations are possible. Langer et al. (1984) point out that the true interstellar ratio must end up somewhere between the values obtained using CO and H_2CO (and CS): the two molecules most extensively used for determining $^{12}C/^{13}C$.

In the galactic disc outside of the GC, there is also a large wealth of useful spectral lines (c.f, Wannier, 1980). One technique using CO isotopic variants has now been extended to over 50 molecular clouds ranging in galactocentric distance from 0.7 to 17.0 kpc (Taylor and Dickman, 1986). These results are consistent with an interstellar $^{12}C/^{13}C$ ratio between 35 to 90 with real apparent variations, but with the bulk of the material having $^{12}C/^{13}C \sim 60$. Interestingly, there is no compelling evidence for a radial gradient, throwing in contrast the low values found in the GC and providing compelling evidence for the GC as having its own unique nucleosynthetic history.

In red giant stars, there have been many determinations of $^{12}C/^{13}C$ using the bands of CN and CC (see, e.g, Scalo, 1977; Lambert, 1976; Fujita and Tsuji, 1976) as well as CO (c.f., Wannier, 1985 and ref.'s therein). The values range from 5 to 60 in G and K giants and 5 to 100 in carbon stars. This range is bracketed by the terrestrial value (90) at the high end and by the equilibrium value CNO cycling value (4) at the low end, which has been taken to indicate enrichment of typical interstellar material with ^{13}C-rich CNO-processed material.

Are the results consistent with a general evolutionary trend? Apparently, yes. The abundance ratio in the GC is less than that in the outer disc, which is less than the solar value. The GC value is, furthermore, more than the values in late-type giant stars which are, in turn, more than can be obtained from CNO processing. This sequence is qualitatively consistent with a scenario in which ^{12}C, from early, massive metal-poor stars is subsequently enriched by ^{13}C from IMS's, either from giant winds or novae. There is no need to invoke a special stellar content in the GC.

5.1.5 $^{16}O/^{18}O$

Extensive results are available from CO, including a survey of doubly rare $^{13}C^{18}O$ form (Linke, 1980) and a map in SgrB2 of $^{13}CO/C^{18}O$ (Lis and Goldsmith, 1989). Additional data are from OH, HCO^+ and H_2CO (Stark, 1981; Kutner et al., 1980; other ref.'s in Wannier, 1980). The GC data are internally consistent and indicate a factor two enhancement of ^{18}O relative to $^{16}O/^{18}O$ in the outer galaxy.

Interestingly, apart from the GC result there is no evidence for a systematic evolution of $^{16}O/^{18}O$. The values in thirteen GMC's in the outer galaxy (Wannier, 1980 and refs therein) and values obtained from fourteen red giant stars (seven Mira's, three carbon, four s-type stars) display significant scatter, but cluster near the terrestrial value of 490 (Wannier, 1985 and ref.'s therein; Wannier and Sahai, 1987). The GC results therefore indicate an enrichment process unique to the GC.

5.1.6 $^{15}N/^{14}N$

The most extensive data come from two surveys: one of HCN in sixteen giant molecular clouds including SgrB2 and SgrA (Wannier et al., 1981) and one in five clouds using NH_3 (Gusten and Ungerechts, 1985). In the GC, the range of $^{15}N/^{14}N$, normalized to the terrestrial ratio is 0.25 to 0.5: less than in the outer disc (0.70 to 0.88), which is in turn less than the solar value (1.0). $^{15}N/^{14}N$ in the GC is, as was true for $^{12}C/^{13}C$, larger than the values in C-stars (0.1-0.5) which are are, in turn, larger than the result of CNO processing. The abundance sequence, consistent with an evolution toward decreasing ^{15}N, has been invoked by Gusten and Ungerechts as indicating that ^{15}N must have a primary nature, forming in massive ($>5M_o$) progenitors as opposed to novae, which are lower in mass. In the GC, they propose that the decrease of $^{15}N/^{14}N$ then results from an influx of secondary ^{14}N from lower-mass stars.

Although the primary/secondary characteristics of ^{14}N and ^{15}N are not clear, the observational results give a clear message: they show a systematic increase in ^{14}N (or decrease in ^{15}N) with increasing exposure to nuclear processing.

5.1.7 $^{17}O/^{18}O$

$^{17}O/^{18}O$ observations yield what may be the most precise of all interstellar (and stellar) abundance ratios and, therefore, is of special interest in examining the GC evolution. Because the abundances of the two rare oxygen isotopes are comparable, the data do not suffer the saturation/excitation effects which can affect species with very different abundances. Also, there are no known isotope fractionation effects for the two oxygen isotopes. The proof of quality is seen from the very small scatter in millimeterwave observations in giant molecular clouds (Table 3). The measures values range from 0.24 to 0.30, with 0.27 being a good typical value (Wannier et al., 1976; Penzias, 1981; Bujarrabal et al., 1983; Guélin et al., 1982).

Is there evidence for evolution of the abundance ratio? Yes, based on stellar observations and the solar value. Values in red giant stars indicate a large, ongoing enrichment of ^{17}O to the interstellar medium. $^{17}O/^{18}O$ has been measured in eighteen stars, including SC stars, C-stars, M-stars and red supergiants (Wannier, 1985 and ref.'s therein). The results are widely scattered (0.4 to 3.1) but interestingly, every single red giant star observed has $^{17}O/^{18}O$ significantly in excess of every single interstellar cloud observed. Furthermore, each of the observed interstellar clouds has $^{17}O/^{18}O$ significantly (3-σ) in excess of the solar value (0.186).

It is therefore a puzzle why the GC observations show no evidence whatever of any evolution relative to the outer galaxy (Table 3). The three values in SgrB2 (using CO, HCO^+ and OH) and the value in SgrA are all consistent (within one σ!) with the 0.28 interstellar average. This does not fit into a simple evolutionary picture.

TABLE 3: $^{17}O/^{18}O$ in Interstellar Clouds

object	$^{17}O/^{18}O$	
Sgr A	.30±.03	CO
Sgr B	.28±.01	CO
	.32±.04	HCO+
	.28±.04	OH
W 33	.27±.01	CO
Cloud 4	.24±.01	CO
K39	.27±.01	CO
W 51	.31±.01	CO
M 17	.29±.03	CO
NGC 6334	.30±.01	CO
DR 21	.28±.02	CO
Ori A	.26±.02	CO
NGC 2024	.26±.02	CO
NGC 2264	.24±.01	CO
W 3	.28±.04	CO
NGC 7538	.26±.03	CO
Solar	0.186	

5.1.8 $^{14}N/^{16}O$

This chemical abundance ratio is difficult to measure accurately due to chemical and physical differences in the two elements. The best determination is from far-IR lines of OI, OII, OIII, and CII. An initial result using NASA's Kuiper Airborne Observatory yields two results in SgrA: consistent with $^{14}N/^{16}O \sim 0.2\text{-}0.4$, or about twice the solar value of 0.12 (Erickson et al., 1989). The value in the outer galaxy is also about 0.1, with no significant radial gradient (Wannier, 1980 and ref.'s therein).

5.2 abundances in the bulge stars and planetary nebulae

Four recent stellar surveys have shed light on GC abundances, respectively using K giants, M giants, C stars and Planetary nebulae. The stellar abundances are of old disc and bulge populations, viewed in places like "Baade's Window", (b=-4 , l=1) where the obscuration is suitably small. Appropriate stellar types must be bright enough to see (giants) but must be such that they can be assumed to sample the gas from which the stars formed. K giants form one of the best classes of stars, but studies also exist of GC M giants and of C stars, not to mention planetary nebulae. We consider only those results which apply to the inner kpc, but the observed stars are seldom located within the inner 500 pc. The heterogeneity of the results no doubt reflects variations in stellar age and/or the abundances in the star-forming clouds.

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A very extensive survey is that of Rich (1986), (see also, Whitford and Rich, 1983), using 100 K giants in Baade's window, located at l~1and b~-4 or about 500 pc from the GC. The K giants are relatively unlikely to have been contaminated by stellar processing and therefore should accurately reflect the abundances prevalent at their era of formation. The resulting spread in metallicity is from 0.1 to 10 times the solar metallicity, with a peak at about double the solar value. The more metal-rich stars have smaller velocity dispersions, interpreted as indicating that these are more centrally condensed and thus, are most typical of stars in the nucleus. They apparently formed later, at smaller radii, in enriched gas. The abundance distribution is found to be fit very well by a simple model of chemical evolution with complete gas consumption.

A second survey is that of Frogel and Whitford (1987) using 185 M giant stars in Baade's Window. Again, there are systematic differences between the GC giants and those in the solar neighborhood, consistent with an excess of heavy elements: in this case, of oxygen which might cause line blanketing in the near-IR. Evidence for a similar metal-enrichment is seen by Azzopardi et al. (1989) on the basis of observations of 33 C-stars in the galactic bulge.

Standing in contrast to these three stellar surveys are ongoing observations of PN in the inner Galaxy. These allow for reliable element abundance determinations, thus complementing results available from GMC's. To date the results are few. One survey has been started based on a selection of 35 PN within 1 kpc (5 degrees) of the GC, with association established by observed radial velocities. O/H and N/H were determined to have approximately solar values in the initial nine objects, based on 3700-7500 Angstrom spectra (Pottasch and Dennefield, 1985). This result is especially interesting in light of reports of galactic gradients in both abundance ratios (Peimbert, 1979 and ref.'s therein). Pottasch and Dennefield conclude that either 1) there is no gradient or 2) it must reverse itself again in the inner Galaxy.

6. CONCLUSIONS AND PROSPECTS

The results of abundance measurements in the GC already provide an interesting picture: sometimes in perfect accord with that expected from model calculations and sometimes at complete odds with the same models.

Observations of stellar abundances in the GC are consistent with a metal enrichment by a factor of a few in the giant population. Both $^{13}C/^{12}C$ and $^{17}O/^{16}O$ are high and there are similar indications for N/O in the gas phase. These results are in accord with the secondary/primary natures of these nuclides. Also, these results fit perfectly into a predicted and observationally verified evolutionary sequence of abundances, lying between 1) the Sun (first) and the outer Galaxy (second) and 2) observed abundances in material processed by red giant stars and partly modified by interior burning. There is also an orderly evolutionary sequence for $^{14}N/^{15}N$, a ratio of two secondary nuclides, demonstrating again that the GC can fit well into the general evolutionary pattern of interstellar abundances.

There are also oddities in the observed abundance ratios. The most outstanding oddity concerns the oxygen isotopes, which apparently provide the most reliable and consistent of all abundance observations. There is an orderly evolutionary progression of $^{17}O/^{18}O$ which, starts with the Solar value, is larger in all observed GMC's in the outer Galaxy, and increases to a higher value in all observed red giant stars. There is, however, no evidence whatever for an evolutionary increase in the GC relative to the outer Galaxy. Apparently, the odd behaviour is due to the ^{18}O nuclide rather than ^{17}O. The oxygen behaviour is not unique. Observations of interstellar He in the GC also seem to be consistent with the general cosmic value (0.1), not what one would expect in highly processed material. In addition, observations of planetary nebulae near the GC show no hint of increase in N/H or O/H relative to the outer Galaxy.

Apparently, new ideas will have to be found, in order to fully incorporate the existing data into existing models of nuclear evolution. But even if that is done, the role of additional observations is clear. The tools exist to expand the list of observed abundances. The GC is heavily obscured, so the emphasis must rest on infrared and radio wavelength spectroscopy. With the construction of new high-altitude observatories and the increased availability of high spectral resolution instruments in balloon and airborne programs, the quality and quantity of data are certain to improve.

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REFERENCES

Audouze, J., Lequeux, J. and Vigroux, L., 1975, Astron. Astrophys., 43, 71.
Azzopardi, M., Lequeux, J. and Rebeirot, E., 1989 (these proceedings).
Bania, T.M., Rood, R.T. and Wilson, T.L., 1987, Ap.J., 323, 30.
Beiging, J., Downes, D., Wilson, T.L., Martin, A.H.M. and Güsten, R., 1980, Astron. Astrophys. (suppl), 42, 163.
Blitz, L. and Heiles, C., 1987, Ap.J. (letters), 313, L95.
Bujarrabal, V., Cernicharo, J. and Guélin, M., 1983, Astron. Astrophys., 128, 355.
Dearborn, D.S.P., Schramm, D.N. and Steigman, G., 1986, Ap.J., 302, 35.
Epstein, R.I., 1977, Ap.J., 212, 595.
Erickson, E.F., Haas, M.R., Colgan, S.W.J., Simpson, J.P., Morris, M.R. and Rubin, R.H., 1989, (these proceedings).
Frogel, J.A. and Whitford, A.E., 1987, Ap.J. 320, 199.
Fujita, Y. and Tsuji, T., 1976, Proc. Jap. Acad., 52, 296.
Geballe, T.R., Krisciunas, K., Lee, T.J., Gatley, I., Wade, R., Duncan, W.D., Garden, R. and Becklin, E.E., 1984, Ap.J., 284, 118.
Gomez-Gonzalez, J., Guélin, M., Cernicharo, J., Kahane, C. and Bogey, M., 1986, Astron. Astrophys., 168, L11.
Guélin, M., Cernicharo, J. and Linke, R.A., 1982, Ap.J., 263, L89.

https://doi.org/10.1017/S0074180900186395 Published online by Cambridge University Press

Güsten, R. and Downes, D., 1980, Astron. Astrophys., 87, 6.
Güsten, R. and Ungerechts, H., 1985, Astron. Astrophys., 145, 241.
Heiligman, G.M., 1988 (private communication).
Henkel, C., Wilson, T.L., Walmsley, C.M. and Pauls, T., 1983, Astron. Astrophys., 127, 388.
Iben, I., Jr. and Truran, J.W., 1978, Ap.J., 220, 980.
Kuiper, T.B.H., Peters, W.L., Gardner, F.F., Whiteoak, J.B. and Reynolds, J.E., 1988, (submitted to Ap.J.).
Kutner, M.L., Machnik, D.E., Tucker, K.D. and Massano, W., 1980, Ap.J., 254, 538.
Lambert, D.L., 1976, Mem. Soc. Roy. Sci. Liege, 9, 405.
Langer, W.D., Graedel, T.E., Frerking, M.A. and Armentrout, P.B., 1984, Ap.J., 277, 581.
Linke, R.A., 1980, (unpublished. See reported values in Wannier, 1980).
Lis, D.C. and Goldsmith, P.F. 1989, (these proceedings)
Pauls, T. and Mezger, P.G., 1980, Astron. Astrophys, 85, 26.
Peimbert, M., 1979, in "The Large Scale Characteristics of the Galaxy", W.B. Burton, ed., Dordrecht: Reidel.
Penzias, A.A., 1979, Ap.J., 228, 430.
Penzias, A.A., 1981, Ap.J., 249, 518.
Pitault, A. and Cesarsky, D.A., 1980, Astron. Astrophys, 82, 203.
Pottasch, S.R. and Dennefield, M., 1985, in "Production and Distribution of C, N, O Elements, I.J.Danziger, F. Matteucci and K. Kjar, eds, ESO workshop Proceedings No. 21, ESO.
Rich, M., 1986, "Abundances and kinematics of K giants in the galactic nuclear bulge", PhD thesis, California Institute of Technology.
Rood, R.T., Steigman, G. and Tinsley, B.M., 1976, Ap.J. (Letters), 207, L57.
Scalo, J.M., 1977, Ap.J., 215, 194.
Stark, A.A., 1981, Ap.J., 245, 99.
Taylor, D.K. and Dickman, R.L., 1986, B.A.A.S., 18, 1026.
Vidal-Madjar, A., Ferlie, R., Gry, C. and Lallement, R., 1986, Astron. Astrophys., 155, 407.
Wannier, P.G., 1980, Ann. Rev. Astron. Astrophys., 18, 399.
Wannier, P.G., Lucas, R., Linke, R.A., Encrenaz, P.J., Penzias, A.A. and Wilson, R.W., 1976, Ap.J. (letters), 205, L169.
Wannier, P.G., Linke, R.A. and Penzias, A.A., 1981, Ap.J. 247, 522.
Wannier, P.G. and Sahai, R.S., 1987, Ap.J. 319, 367.
Wannier, P.G., 1985, in "Production and Distribution of C, N, O Elements", J. Danziger, ed., ESO.
Whitford, A.E. and Rich, R.M., 1983, Ap.J. 274, 723.

https://doi.org/10.1017/S0074180900186395 Published online by Cambridge University Press