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THE METAL CONTENT OF GALACTIC WINDS

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RESUMEN

Buena parte de la formación estelar en el universo local, y quizás la mayor parte de la formación estelar a altos corrimientos al rojo, ocurre en galaxias con brotes estelares. La gran densidad espacial y temporal de SNe en las galaxias con brotes alimenta flujos de gas interestelar a escalas galácticas. Estos flujos han sido observados en galaxias con diferentes masas y las tasas de pérdida de masa por estos flujos son del mismo orden que las tasas de formación estelar. Reseñaré algunos resultados del análisis de las imágenes espectrales del Chandra. La principal implicación es que los vientos calientes en brotes de formación estelar en enanas transportan hacia el medio intergaláctico la mayor parte de los elementos pesados producidos por el brote.

ABSTRACT

A significant fraction of the star formation in the local universe, and perhaps the majority of star formation at high redshift, occurs in starburst galaxies. The high spatial and temporal density of SNe in starburst galaxies fuels galactic-scale outflows of interstellar gas. These outflows have been observed in galaxies over a broad mass range, and the estimated mass outflow rates are of the same order as the star formation rates. I will review new results from the analysis of Chandra spectral imaging data. The main implication is that the hot winds in dwarf starbursts carry most of the heavy elements produced by the starburst into the intergalactic medium.

Key Words: **ISM: — IGM: — X-RAYS — STARBURST — CHEMICAL EVOLUTION**

1. INTRODUCTION

The supernova explosions which power galactic winds are believed to disperse elements synthesized by massive stars. Yet observations show little localized enrichment in HII regions (Kobulnicky & Skillman 1997; Martin 1996). Could the hot phase of the outflow carry the oxygen and other alpha-process elements, synthesized by the starburst?

For several decades now, theorists have argued that winds carry heavy elements out of galaxies, and that they remove a larger fraction of the metals in lower mass galaxies (Larson 1974; De Young & Gallagher 1990; Dekel & Silk 1986; Lynden-Bell 1992). Only recently, however, has it become possible to directly measure the metal content of galactic winds.

2. MEASUREMENTS OF HOT PHASE METALLICITY

Metal abundances derived from thermal X-ray spectra have a controversial history due to uncertainties in the atomic physics, different definitions of the solar abundance, and a number of degeneracies inherent to multi-component spectral models. Reports of very sub-solar abundances in elliptical galaxies, for example, were met with skepticism, and have been traced in part to uncertainties in the Fe-L shell atomic physics (Liedahl et al. 1995). A degeneracy

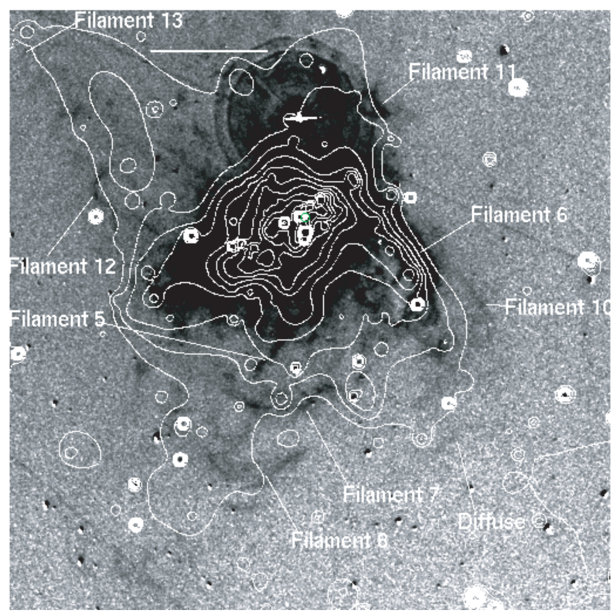

Fig. 1. Contours of 0.3-6 keV X-ray emission on Hα image. The contours are spaced by a factor of 1.347 from 0.00594 to 1.696 cnts s $^{-1}$ per square arcminute. The Hα image is displayed on logarithmic scale, and the filaments identified by Hunter et al. (1993) are marked. White bar represents $1'.0$.

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between high metallicity, two-temperature models and low metallicity, single-temperature models has also produced reports of surprisingly low metallicities (Buote & Canizares 1994). In spectra of galaxy clusters, relative abundances have proven difficult to constrain owing to blends between Fe-L lines and lines from alpha-process elements (Mushotzsky et al. 1996). Hence, the metallicities tend to be pushed lower than their true value if the temperature range is not fully represented. Weaver et al. (2000; see also Dahlem et al. 1998), pointed out that omission of intrinsic absorption from a spectral model could erroneously produce supersolar $[\alpha/Fe]$ ratios because the apparent strength of Mg and Si lines would increase relative to Fe-L lines.

These ambiguities can now be resolved using Chandra data with the support of optical and radio observations. Martin, Kobulnicky, and Heckman (2002) present the analysis of the dwarf starburst NGC 1569 (SFR 0.17 $M_\odot$ yr^{-1}) – see Figure 1. The low metalliciy of the galaxy, HII region $O/H \sim 0.20$ $(O/H)_\odot$, is ideal for contrasting the metallicity of the hot and warm gas phases. The proximity of the galaxy, 2.2 Mpc, indicates this system is not particularly unusual.

The Chandra spectrum of NGC 1569 is complex and cannot be described by a single component emission model. The color X-ray image, coded by photon energy (Fig. 8 Martin, Kobulnicky, & Heckman 2002) directly reveals the necessary model components. First, the image clearly shows the discrete sources have harder spectra than the diffuse emission. The discrete source contribution to the integrated spectrum can be fitted independently with a simple absorbed power law model. Secondly, the image confirms the disk emission is hotter than the halo emission (Della Ceca et al. 1996) as shown by ROSAT data. At the higher spatial resolution, however, we discover a hardness gradient across the inclined disk which is well described by intrinsic photoelectric absorption. Addition of intrinsic absorption components to each temperature component requires the fitted ratio of alpha elements to Fe to exceed 25% of the solar value.

A degeneracy between the fitted metallicity and the continuum normalization does not allow a firm upper limit to be placed on the metallicity from the spectral fitting alone. Since the spectrum includes the OVII and OVIII lines, which are at lower energy than the Fe-L complex, the data strongly constrain the alpha element to Fe abundance ratio. Fig. 2 shows the fitted α/Fe ratio is about one-third the solar ratio. That the alpha element enhancement is weak relative to pure Type II supernova ejecta is not surprising because the dynamical models predict cooler disk clouds are entrained in the flow.

Fig. 3 illustrates a simple mixing model that predicts the O/Fe abundance ratio and the wind metallicity for various amounts of mass loading. In the limit of no mass loading, the wind would carry only the supernova ejecta. As the mass loading increases (toward the right), the O and O/Fe values decrease toward their values in the ambient ISM. The data points show the best-fit values of O/H and O/Fe from the X-ray spectrum. They imply mass loading factors of 9 and 20, which are consistent given the uncertainties in each value. The implied mass of X-ray emitting gas is 3.5×10^6 $M_\odot$ in the solar metallicity model, so the wind carries $\sim 34,000$ $M_\odot$ of oxygen.

The fitted spectral models define a tight relation between the mass of X-ray emitting gas and the metallicity. For higher wind metallicity, the fitted models require a lower continuum normalization; and the inferred wind mass decreases. It follows that each solution for the mixing parameter and wind metallicity also corresponds to a specfic amount of supernova ejecta in the flow. The oxygen abundance of the hot wind must be less than twice the solar oxygen abundance. Otherwise, the implied M_{ej} is higher than the upper limits allowed by the star formation history and evolutionary synthesis modeling. Considering the lower limit on the wind metallicity derived from the spectral fitting, the wind metallicity is well constrained to within a factor of 2 to 4.

It is interesting to compare the metal mass carried by the wind to the total metal yield of the starburst in NGC 1569. The SB has formed stars continuously for 10-20 Myr. Integration of the Woosley & Weaver yields over a Salpeter IMF and scaling to the starburst strength gives a yield 25,000 to 51,000 $M_\odot$ of O. This pollution starts after a few Myr and is complete 40 Myr after the bursting period ends. The mass of oxygen produced by the current starburst is the same as the mass of oxygen in the wind to within the measurement errors. The wind therefore appears to carry nearly all the heavy elements synthesized by the massive stars *in the starburst.*

3. FATE OF METAL ENRICHED WINDS

The sound speed in the 0.7 keV component of the hot wind in NGC 1569 is 430 km s^{-1} . As the superbubble shells fragment, the wind likely accelerates toward a terminal velocity $\sim \sqrt{3}c_s \sim 740$ km s^{-1} . The escape speed from the halo of NGC 1569 is $\sim 3v_{rot} \sim 100$ km s^{-1} , so it seems unlikely that

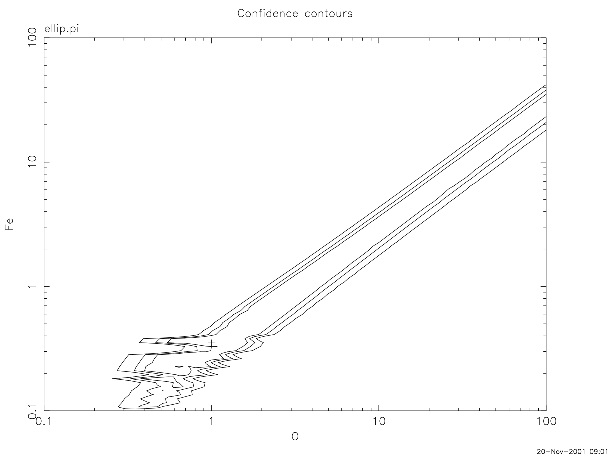

Fig. 2. Elemental abundances fitted to the spectrum of the diffuse gas. The cross marks the best fit. Contours represent the 60%, 90%, and 99% confidence levels. The O/H and Fe/H abundance ratios are shown relative to the solar photospheric values of Anders & Grevesse (1989). On the more common solar meteoritic scale, the relative Fe abundances are 0.085 dex higher. Note the Mg, Ne, Si, and Ca abundances are tied to O, and the other metals vary with the Fe abundance.

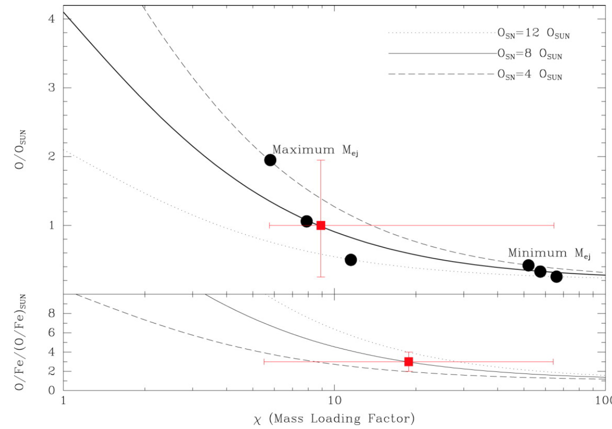

Fig. 3. Mixing models for mass entrainment in the wind. Three tracks illustrate the plausible range of supernova yields. The Chandra measurements for O and O/Fe are shown. The solid circles delimit the mass of stellar ejecta produced by the starburst model after a time of 10 Myr and 20 Myr. Consistent models require substantial mass loading.

the metals carried by the hot wind would return to the galaxy.

Figure 2 of Martin (1999) and Figure 12 of Heckman et al. (2000) compare the X-ray temperatures of galactic winds to the rotational speeds for many galaxies. It is interesting that the measured X-ray temperatures of winds show little correlation with the depth of the gravitational potential. The hot winds appear destined to escape from the dwarf starburst galaxies with $v_{rot} \lesssim$ 130 km s^{-1} (Martin 1999); but the bulk of the X-ray bright component probably remains bound to the more luminous galaxies. Although an extremely diffuse component of hotter gas could escape detection in the luminous starbursts, numerical simulations indicate this component would carry little mass (Strickland & Stevens 2000).

4. IMPLICATIONS OF METAL LOSS IN DWARF STARBURST WINDS

The potential impact of galactic winds on the chemical properties of galaxies was described by Larson (1974) several decades ago. He predicted a strong correlation between galactic mass and metallicity over the mass range where winds escape and constant metallicity among more massive systems. Measurements of stellar metallicity in elliptical galaxies (Faber 1973; Brodie & Huchra 1991) established that such a relation exists. Over roughly the same period, emission-line measurements revealed a similar mass – luminosity trend among gas-rich irregular galaxies (Lequeux et al. 1979; Skillman et al. 1989).

No consensus was ever reached, however, as to whether the low metallicity of dwarf galaxies reflects the selective loss of metal-enriched gas or simply the delayed gas consumption in these systems. The Chandra observations of NGC 1569 leave little doubt that dwarf starburst winds can remove metals almost as efficiently as they are created. It is currently not known what fraction of the stars in a typical dwarf galaxy formed in a starburst phase however. The X-ray absorption model for NGC 1569 indicates the cold disk has been enriched with heavy elements, and it holds a larger mass of oxygen than the wind carries. The mass of metals ejected could be less than that produced over a Hubble time if a large fraction of stars were formed in a more quiescent mode of star formation. Simple, but reasonable, extensions of our knowledge of the fraction of stars formed in starbursts and the scaling between the retained gas fraction and the potential depth are consistent with significant enrichment of the IGM by starburst winds Heckman et al. (2000).

A most recent compilation of data for gas-rich galaxies by Garnett (2002) reveals a turnover in the metallicity at rotation speeds (i.e. galaxy masses) between 100 and 200 km s^{-1} . The contribution to this proceedings by Heckman describes a similar mass - metallicity relation derived from a large, presumably unbiased, sample of galaxies observed by the Sloan Digital Sky Survey. This turnover appears at essentially the same galactic mass as was described above for the retention of hot starburst winds.

The observed threshold for galactic mass loss and the direct detection of metal-enriched winds strengthen claims that metal-enriched winds are the dominant factor in establishing the mass-metallicity relation among galaxies. The low effective yields in dwarf galaxies, relative to luminous galaxies, provide further evidence that youth alone is unlikely to explain the low abundances in dwarf galaxies (Garnett 2002).

5. IMPROVEMENTS IN MEASUREMENTS

More measurements of the metal content, dynamics, and temperatures in nearby galactic winds will clearly be needed to establish the nature of the transition from metal ejection to metal retention. It will not be possible to measure wind metallicities in large samples of galaxies with the current generation of X-ray telescopes however. The next major step forward will likely come from measuring abundances from UV resonance absorption lines whose kinematics reveal association with the winds. Measurements of the metallicity in the outer parts of galactic disks would also greatly improve our understanding of chemical recycling. It will also be important to establish how galaxy environment affects the fate of the winds. Metals stripped from relic winds during cluster infall could be important for the enrichment of the intracluster medium.

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