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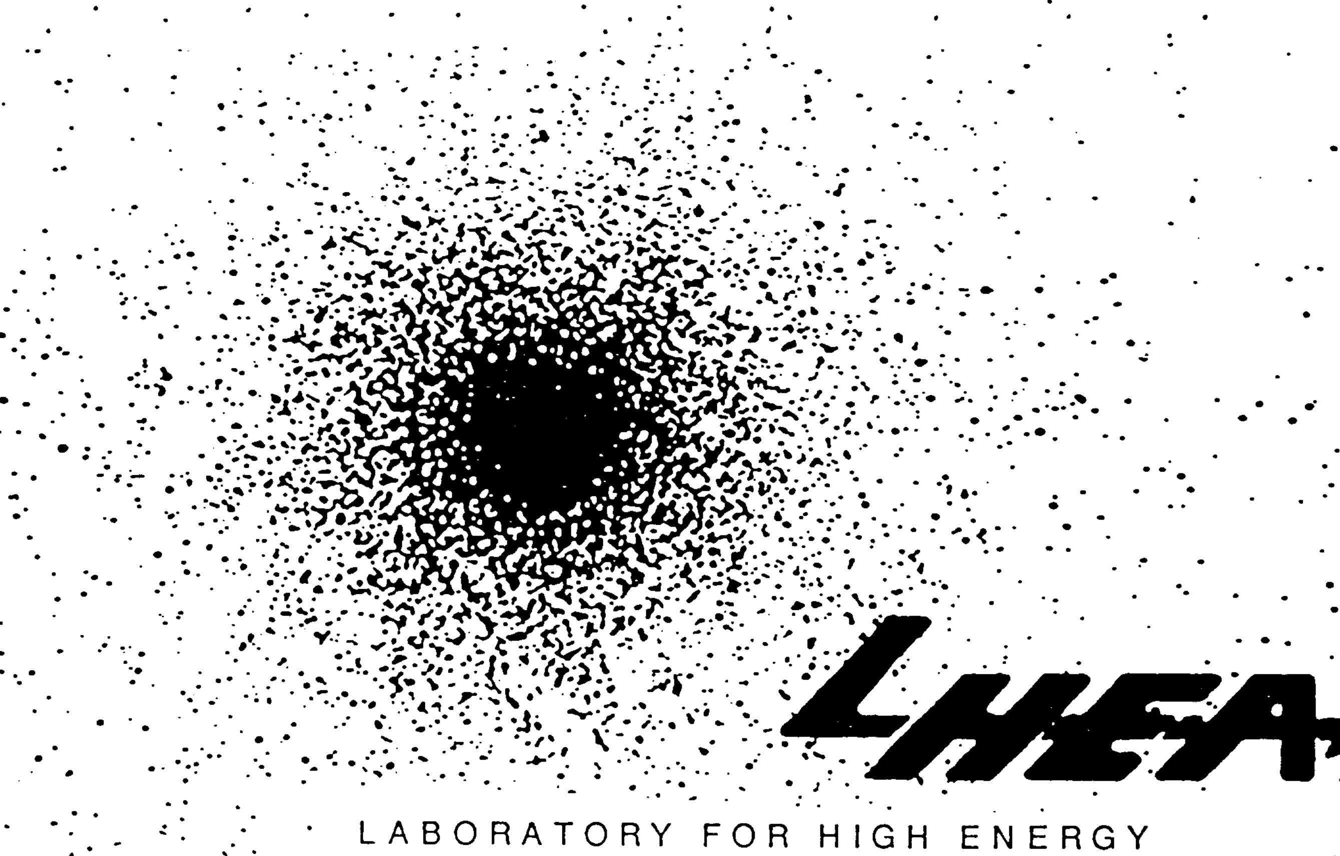

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DISCOVERY AND IMPLICATIONS OF VERY LOW METAL ABUNDANCES IN NGC 1404 AND NGC 4374

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ABSTRACT

We present our analysis of *ASCA* PV phase observations of the elliptical galaxies NGC 1404 and NGC 4374 (M84). The average metallicities in the hot gas derived from the SIS spectra are exceptionally low, $Z \sim 0.15$ solar, while the temperatures are "typical", $kT \sim 0.75$ keV. We also place upper limits on intrinsic column densities. The low abundances lend support to the theory of Fe enrichment of intracluster media by protogalactic Type II supernova-driven winds, and raise the possibility of a fundamental connection between baryon fraction, dissipation, and abundances in elliptical galaxies.

Subject headings: galaxies: abundances – galaxies: individual (NGC 1404, NGC 4374) – galaxies: formation – dark matter

1. INTRODUCTION

Formative and early evolutionary processes in elliptical galaxies leave their imprint not only on the kinematics and morphology of these systems, but also on the elemental abundances of their constituent stars.

Broad and narrow band optical photometry, and absorption line studies have been used to infer stellar abundances and gradients out to ~one effective radius (R_e; e.g., Gorgas et al. 1990, Davies et al. 1993, Schombert et al. 1993 – hereafter S93). The line strengths and color indices used in these optical investigations are generally indirect measures of stellar metallicity, requiring assumptions about the stellar population (age, initial mass function, abundance ratios) for the conversion to Fe/H[1] (Buzzoni et al. 1992). Because post-main sequence stellar mass loss is very efficiently converted into $\sim$ 1 keV gas (Mathews 1990), the advent of moderate resolution imaging X-ray spectroscopy provides an opportunity to directly measure the metallicities of stars in elliptical galaxies. The abundances in the hot gas, and hence in the stars from which the gas originates, are derived from model fits to the X-ray data for those elements with prominent emission features in the X-ray band. A great advantage of X-ray spectroscopy over optical methods is that abundances can be easily measured out to many R_e. Complications arise in the interpretation of the X-ray derived abundances as a result of the modest spatial resolution of these measurements, possible contamination from supernovae and accretion of intergalactic gas, and the effects of gas flows (see below).

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[1] In this *Letter* we use Fe/H to refer to the metallicity of stars (Fe abundance in solar units), and Z to refer to the metallicity of hot gas relative to solar. The hot gas is assumed to have solar ratios (see below); in any case the determination of Z is primarily driven by the abundance of Fe.

The first investigation of this kind was the BBXRT observations of NGC_1399 and NGC 4472 (Serlemitsos et al. 1993). Surprisingly, sub-solar metallicities were discovered in the hot gas in these galaxies, severely constraining the Type Ia supernova (SNIa) rate. A more extended sample of early-type galaxies is becoming available via observations with the *ASCA* satellite. The analysis of three galaxies in the Virgo cluster, including NGC 4472, has confirmed and extended the BBXRT result: abundances of Fe and other elements were found to be ~ 0.5 solar (Awaki et al. 1994; hereafter A94).

In this *Letter*, we report results for two elliptical galaxies observed with *ASCA*, NGC 1404 and NGC 4374 (M84), that are distinguished from the A94 sample by their compactness at optical and X-ray wavelengths. Our main result is that we find abundances that are significantly lower than were presented in A94. These abundances are so low that we are led to question some basic assumptions about the history of the hot gas and even of the galaxies themselves, as well as the origin of metals in intracluster media (ICM).

2. OBSERVATIONS AND EXTRACTION OF SIS SPECTRA

We have used PV phase observations of the Fornax and Virgo clusters. Neither galaxy was the primary target of observation. The data for NGC 1404 were obtained during the two observations of the Fornax cluster with the SIS in 4-CCD mode. The net good times for both the SIS and GIS were 21.6 and 21.1 ks for the two pointings. We obtained data for M84 from the pointing toward M86. The SIS was predominantly in 2-CCD mode. The total good time was 21.1 ks for both the GIS and SIS. Both sources are small; $3'$ radius extraction regions were used to maximize the source flux and minimize the contamination from surrounding cluster gas.

Because both NGC 1404 and M84 are embedded in bright cluster emission we have used "local" background for the analysis. For NGC 1404 we have used a region $7'$ to the north that is the same angular distance from NGC 1399. For M84 we have used a position mid-way between M84, M86, and NGC 4388 that has comparable Virgo diffuse counting rates to the proximity of M84. The background subtracted SIS counting rates are 0.045 ct s^{-1} for NGC 1404 and 0.036 ct s^{-1} for M84. The 0.5-4.5 keV fluxes from the GIS are 2.4 10^{-12} erg cm^{-2} s^{-1} for NGC 1404 and 2.1 10^{-12} erg cm^{-2} s^{-1} for M84, while the 0.2-2.0 keV flux from the *ROSAT* PSPC for NGC 1404 is 2.5 10^{-12} erg cm^{-2} s^{-1}.

3. SPECTRAL ANALYSIS RESULTS

We have fit the SIS and GIS spectra of NGC 1404 and NGC 4374 with an absorbed single-temperature Raymond-Smith thermal plasma (R-S) model where the column density, metallicity, and temperature are free parameters. The SIS-0 spectrum of NGC 1404 and best-fit model are shown in Figure 1. The best-fit parameters and 90% confidence errors are displayed in Table 1 along with various other quantities of interest. Confidence contours at $\Delta\chi^2 = 2.71, 4.61$, and 9.21 are shown in Figures 2a and 2b. The addition of a hard component does not improve the spectral fits, providing we use the local cluster as background (see above, and Matsushita et al. 1994). Analysis of *ROSAT* archival data for NGC 1404 results in a very similar temperature and abundance. For both objects there is only marginal agreement with the much less accurate Einstein IPC temperatures (Kim et al. 1992).

The column density of NGC 4374 is consistent with the Galactic value of 2.6 10^{20} cm^{-2}; however, there may be a small excess over the Galactic column of 1.3 10^{20} cm^{-2} in NGC 1404. The temperatures of the hot gas in NGC 1404 and NGC 4374 are very similar to those in NGC 4406 and NGC 4636 (A94), $kT = 0.6$-0.8 keV. This is surprising since the stellar temperatures derived from central stellar velocity dispersions range over more than a factor of two for these four galaxies. A94 noted the good agreement between

$\beta_{image} \equiv \mathrm{dlog}\rho_{gas}/\mathrm{dlog}\rho_{stars}$ and $\beta_{spec} \equiv T_{stars}/T_{gas}$ that are equal if both the stars and gas are isothermal and in hydrostatic equilibrium, and the stars are on isotropic orbits. Using the optical surface photometry of Caon et al. (1994) and fitting public *ROSAT* PSPC images to obtain β_{image}, we find that β_{image} may exceed β_{spec} by a factor ~ 1.5 for both galaxies (Table 1); more careful spatial analysis is needed to confirm this. This is also the case for NGC 4636 if we adopt the velocity dispersion of Bender et al. (1992), although there remains no discrepancy for NGC 4406 and NGC 4472. Also shown in Table 1 are approximate mass-to-light ratios, assuming the gas is isothermal. These values are noticeably lower than in the A94 galaxies solely because we do not detect gas out to as large a radius. More accurate dark matter constraints require a more complete, joint treatment of *ASCA* and *ROSAT* data (e.g., Mushotzky et al. 1994).

The most striking feature of the best fit models are the low abundances, $Z = 0.14$ (0.11-0.17 at 90% confidence) for NGC 1404 and $Z = 0.14$ (0.10-0.22) for NGC 4374, abundances significantly lower than were found by A94 for NGC 4472, NGC 4406, and NGC 4636. Mewe-Kaastra thermal plasma models yielded very similar abundances to R-S models, but temperatures ~ 0.2 keV lower. R-S models with variable relative abundances were also fit to the data: abundance ratios are consistent with solar. For NGC 1404, the 90% confidence limits on the abundances, relative to solar, of Fe, Si, and O are 0.089-0.136, 0.080-0.27, and 0.14-0.42, respectively.

4. DISCUSSION

4.1 The Origin of the Hot Gas and its Heavy Elements

There are two obvious non-stellar sources that could alter the abundances in the hot gas. Type Ia supernovae can enhance the Fe abundance relative to other elements

(Loewenstein & Mathews 1991). A SNIa rate at the lower end of the range of rates in early-type galaxies would enhance the Fe abundance to ~solar – far in excess of the upper limit from *ASCA*. Clearly, the presence of SNIa would only serve to exacerbate the problem of low Z. Moreover, Fe is not enhanced relative to O as would be expected if a significant fraction of the Fe were ejected from SNIa.

Accretion of low metallicity intergalactic gas can, on the other hand, dilute Z. However, the amount of hot gas observed is generally consistent with the accumulation of stellar mass loss over the past few billion years and any accreted material would add to this. If accretion of low metallicity gas causes the low hot ISM metallicities, one expects an anti-correlation of L_X/L_{OPT} with Z that is not observed in the small *ASCA* sample of galaxies. Alternatively, NGC 1404 and NGC 4374 could have recently fallen into their respective cluster cores, been stripped of their stellar mass loss, and then accreted low-metallicity intracluster gas. However, the hot gas metallicities in NGC 4374 and NGC 1404 are even lower than in the clusters where they reside (from GIS observations of the Virgo and Fornax clusters).

Therefore, we conclude that our measurements of Z are true reflections of stellar abundances in NGC 1404 and NGC 4374.

4.2 Abundance Gradients and Galaxy Formation

Post-main sequence stars on the red and asymptotic giant branches are responsible for most of the optical light, and hence the optical metallicity indicators, as well as the majority of the mass loss that ends up as X-ray emitting gas (Renzini & Buzzoni 1986). This is independent of the assumed IMF, and depends only on assumptions about stellar structure and evolution.

However, the optical and X-ray measurements sample stars at different positions in the galaxy, a significant factor if abundance gradients are present. Such gradients are seen in the Mg_2 index. Assuming solar abundance ratios, Fe/H is inferred to decrease from 2-3 near the center to ~ 1 at 0.5-1.0R_e (Gorgas et al. 1990). Since Mg is produced primarily in Type II supernovae, this may not be a true measure of the abundance of Fe (Worthey et al. 1992), which is produced primarily in Type I supernovae and is more relevant to a comparison with Z. There may also not be a constant [Mg/Fe] ratio either within a single galaxy (Stiavelli & Matteucci 1991) or among galaxies of different mass (S93). Using narrow band photometry of a sample of elliptical galaxies, S93 find core Fe/H values between 0.3 and 1.3 dropping to < 0.1 at the Holmberg radius, with an average $\Delta[\text{Fe/H}]/\Delta\log r = -0.48$.

The *ASCA* abundance measurements are complicated averages over $\sim 3'$ apertures, corresponding to $\sim 7R_e$ and $\sim 3R_e$ for NGC 1404 and NGC 4374, respectively. For NGC 4374, S93 find Fe/H$\sim$ 0.3 from J-K photometry averaged over $\sim 0.5R_e$. This is consistent with our measurement of Z if the mild abundance gradient reported in S93 persists out to $3R_e$. On the other hand, more direct spectroscopic measurements of Fe/H in NGC 4374 (Gonzalez et al. 1994) yield Fe/H=0.6-0.9 at R_e as well as $\Delta[\text{Fe/H}]/\Delta\log r = -0.24$ (from the center out to R_e). This is marginally consistent with our 99% confidence upper limit on Z if the metallicity gradient steepens considerably beyond R_e. The abundances in the hot gas could be lower than in the stars if there is inflow with a centrally concentrated mass sink (Loewenstein & Mathews 1991), or if incomplete mixing results in relatively metal-rich inhomogeneities that preferentially "cool out" of the hot gas (J. N. Bregman, private communication).

We believe that a difference in scale, in conjunction with the presence of negative metallicity gradients, is an important factor in explaining why Z is lower in NGC 1404 and NGC 4374 than in other elliptical galaxies observed with *ASCA*. Since the determinations of Z are averages over apertures of similar physical size, but different size in units of R_e (R_e for NGC 1404 and NGC 4374 are 1.9 and 4.5 kpc, respectively, compared to 7.5-8.6 kpc for NGC 4406, NGC 4472, and NGC 4636 (Bender et al. 1992)), if the light and metallicity scale lengths are proportional we have sampled out to radii with lower abundances in NGC 1404 and NGC 4374. So, the low abundances seen in NGC 1404 and NGC 4374 may be due, in part, to a continuation (or perhaps steepening) of the gradients observed at optical wavelengths on a smaller scale. We thus predict a negative gradient in the metallicity of X-ray emitting gas in the A94 galaxies. And indeed, in NGC 4636 a decline in Z from ~ 0.35 averaged over the inner R_e to 0.1 in annuli centered beyond $\sim 4.5R_e$ from the center is found (Mushotzky et al 1994). For NGC 4636, Z averaged over the same aperture *in units of R_e* used for NGC 1404 and 4374, is 0.25 and 0.3, respectively – more in line with the measurements presented in this paper, but still somewhat higher.

The lower metallicities in NGC 1404 and NGC 4374 may be a reflection of fundamental intrinsic differences. NGC 1404 and NGC 4374 are more compact optically than the A94 galaxies, and therefore have undergone more dissipation. They are also more compact in X-rays, from which we infer a smaller mass-to-light ratio. This leads us to speculate that elliptical galaxies with a larger baryon fraction undergo more dissipation and also are more susceptible to mass loss during their era of star formation. This enhanced mass loss could truncate the star formation process at large radii, resulting in stars, and hence hot gas, of low metallicity. A trend of increasing Fe/H, derived from the J-K indices of S93, with decreasing R_e (or increasing optical surface brightness at R_e) is in accord with this (Franx and Illingworth 1990).

Fe/H measured near the centers of elliptical galaxies may not always be representative of the galaxy as a whole – in the merger scenario for elliptical galaxy formation the stars in the vicinity of the center form from gas that lost its angular momentum and subsequently formed stars, possibly through several enrichment cycles (Bender & Surma 1992). We note that the low elliptical galaxy metallicities we have measured preclude their formation by the *recent* merger of spiral galaxies.

4.3 Enrichment of Intracluster Gas

The low metallicities have important implications for the origin of the metal enrichment of the ICM. Two mechanisms for producing the large masses of Fe found in the ICM from the observed number of early-type galaxies have been proposed. (1) A prolonged period of SNIa activity and outflow of stellar mass loss into the ICM would inject Fe-enriched gas into the ICM, but would also leave a long-lived Fe enhancement in the hot gas remaining in the galaxy (Renzini et al. 1993, Mihara & Takahara 1994) – even if the SNIa rate is much lower now than in the past (Loewenstein & Mathews 1991). The very subsolar abundances reported here rule out such a model. Alternatively, (2) Type II supernova-driven winds in the early life of the galaxy could be the primary enrichment mechanism. This requires either a flat or bimodal IMF (Arnaud et al. 1992, Arnaud 1994). The abundance ratios derived from preliminary analysis of the ICM in several clusters are in good agreement with those expected from SNII enrichment (Mushotzky 1994). In light of our results, these models have evidently aimed to reproduce amounts of Fe in the stellar and gaseous components in elliptical galaxies that are overestimated by factors of $\sim$ 3-10. Contrary to the assumptions of these models, in order to accommodate both ISM and ICM Fe abundances, most ($>80\%$) of the Fe produced during the early history of these galaxies must be ejected, and relatively little locked into stars. This suggests that high mass star formation and ejection of enriched gas into the ICM continued after the formation of the low metallicity main body of stars. The relatively metal-rich cores of elliptical galaxies may be a by-product of this continued star formation.

5. SUMMARY

We have derived the metallicities and temperatures of the hot gas in the elliptical galaxies NGC 1404 and NGC 4374 (averaged over $7R_e$ and $3R_e$, respectively) from data obtained with the *ASCA* SIS. We emphasize that these values are determined primarily by the Fe L blend that peaks at $\sim$ 0.8 keV, and are independent of assumptions about the column density or the presence of a hard component. The gas temperatures, $kT \approx 0.75$ keV, are very similar to those of NGC 4406 and NGC 4636 and are too high to be bound by the stellar gravitational potential alone, thus requiring the presence of dark matter.

The metallicities are < 0.3 solar at 99% confidence. We propose that metallicity gradients observed optically inside R_e persist and perhaps steepen beyond R_e, thus reconciling the *ASCA* measurements with other abundance determinations in these and other elliptical galaxies – $\sim$ 0.3-1.0 solar Fe abundances in the X-ray emitting gas (A94) and stars (Gonzalez et al. 1994) within R_e, and low stellar Fe abundances at the Holmberg radius (S93). The detection of a very extensive metallicity gradient in NGC 4636 corroborates this (Mushotzky et al. 1994). Theories that seek to explain the formation of elliptical galaxies and the enrichment of the ICM must take these low abundances and gradients into account.

The ubiquity of abundance gradients throughout the fundamental plane indicates that dissipative collapse must be a fundamental process in the formation and early evolution of elliptical galaxies of all sizes, despite arguments that it is unimportant relative to stellar component dominated mergers for giant ellipticals (Kormendy 1989, Bender et al. 1992). Galaxies such as NGC 1404 and NGC 4374 may have a relatively large ratio of baryonic to nonbaryonic matter, resulting in more dissipation and more mass loss during the star formation epoch. This mass loss can cut off star formation at large radii, resulting in steep metallicity gradients and low average hot gas abundances.

However, the star formation cycle must persist at small radii to account for ~solar central metallicities and the ejection of large amounts of Fe into the ICM.

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Table 1
Optical and X-ray Parameters of Interest

galaxy (NGC)	L_B^1 ($L_{B\odot}$)	σ^1 (km s^{-1})	R_e^1 (kpc)	L_X^2 (erg s^{-1})	N_H^3 (cm^{-2})	Z^4 ($Z_\odot$)	kT (keV)	β_{image}	β_{spec}	M/L_B^5 ($M_\odot/L_\odot$)
1404	1.5 10^{10}	225	1.9	8.9 10^{40}	$5.2^{+2.1}_{-2.2}$	$0.14^{+0.03}_{-0.03}$	$0.75^{+0.03}_{-0.03}$	0.62	0.42	40
4374	4.2 10^{10}	287	4.5	5.5 10^{40}	$1.8^{+5.3}_{-1.8}$	$0.14^{+0.08}_{-0.04}$	$0.74^{+0.05}_{-0.06}$	$\sim$ 1.0	0.69	24

1) from Bender et al. (1992), assuming a distance of 15 Mpc to NGC 1404 and 17 Mpc to NGC 4374

2) from Fabbiano et al. (1992)

3) column density in units of 10^{20} cm^{-2}

4) metallicity in solar units assuming solar abundance ratios

5) ratio of total mass to blue light within 3′

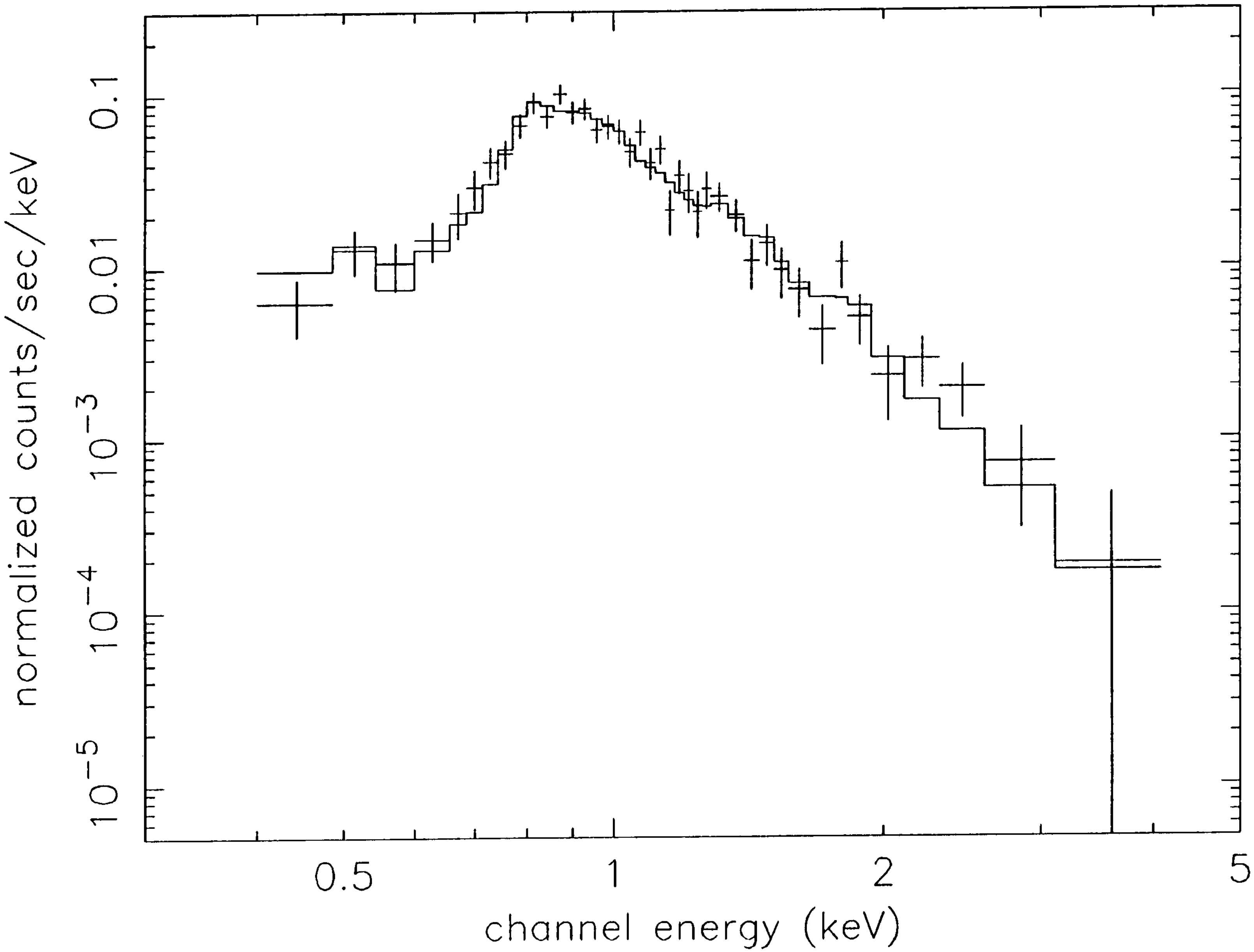
FIGURE CAPTIONS

Fig. 1.– SIS-0 source spectrum of NGC 1404 and best-fit absorbed R-S model (see Table 1).

Fig. 2.– (a) Confidence contours in the temperature-abundance plane for absorbed R-S model simultaneous fits to SIS-0 and SIS-1 spectra of NGC 1404. The best fit is shown as a plus sign, and the contours are $\Delta\chi^2 = 2.71, 4.61.$ and 9.21. (b) same as (a) but for NGC 4374 and including the GIS spectrum in the fit.

FIG. 1

ASCA SIS0 DATA FOR NGC 1404



richard 7-Jul-1994 10:3

FIG. 2A

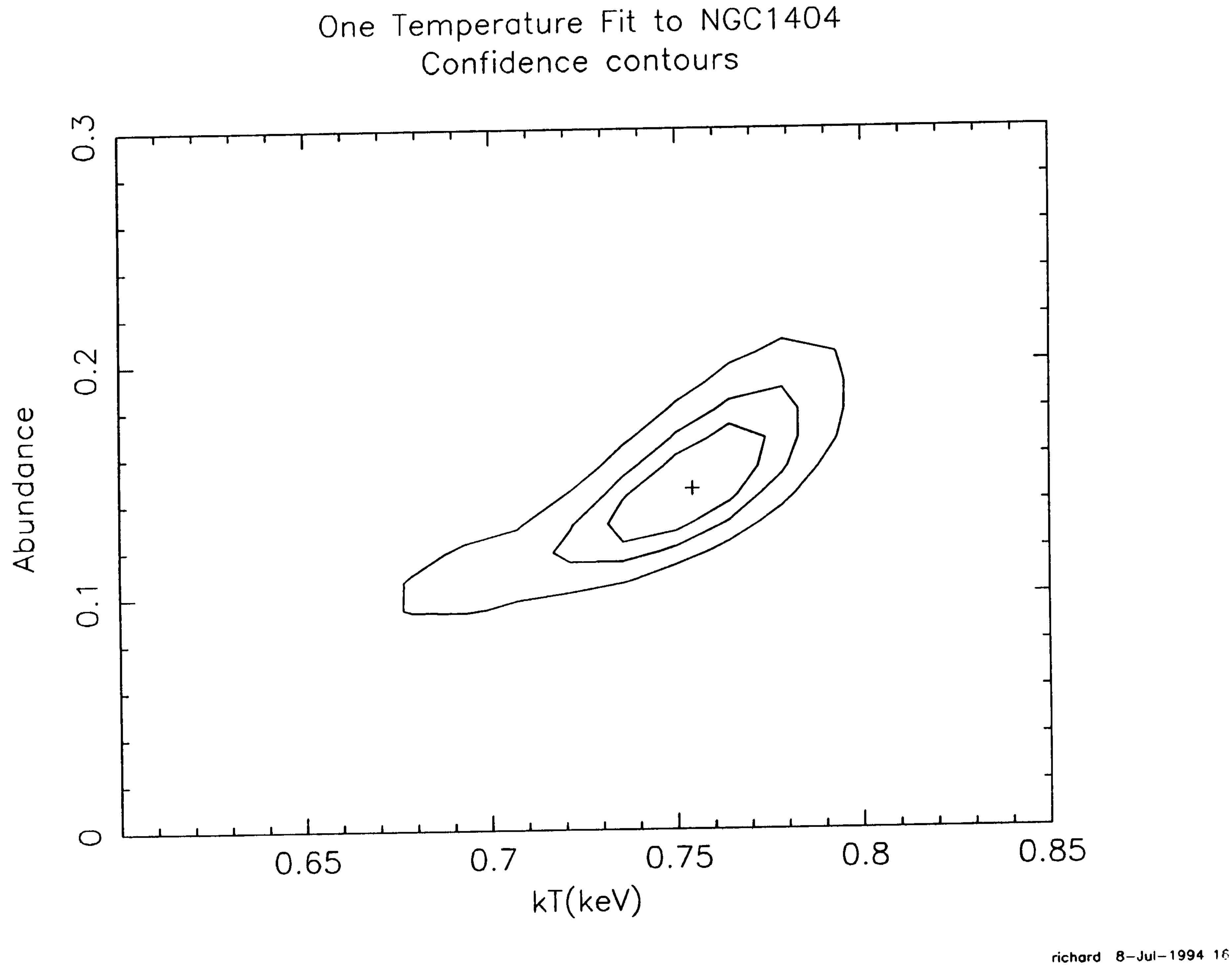
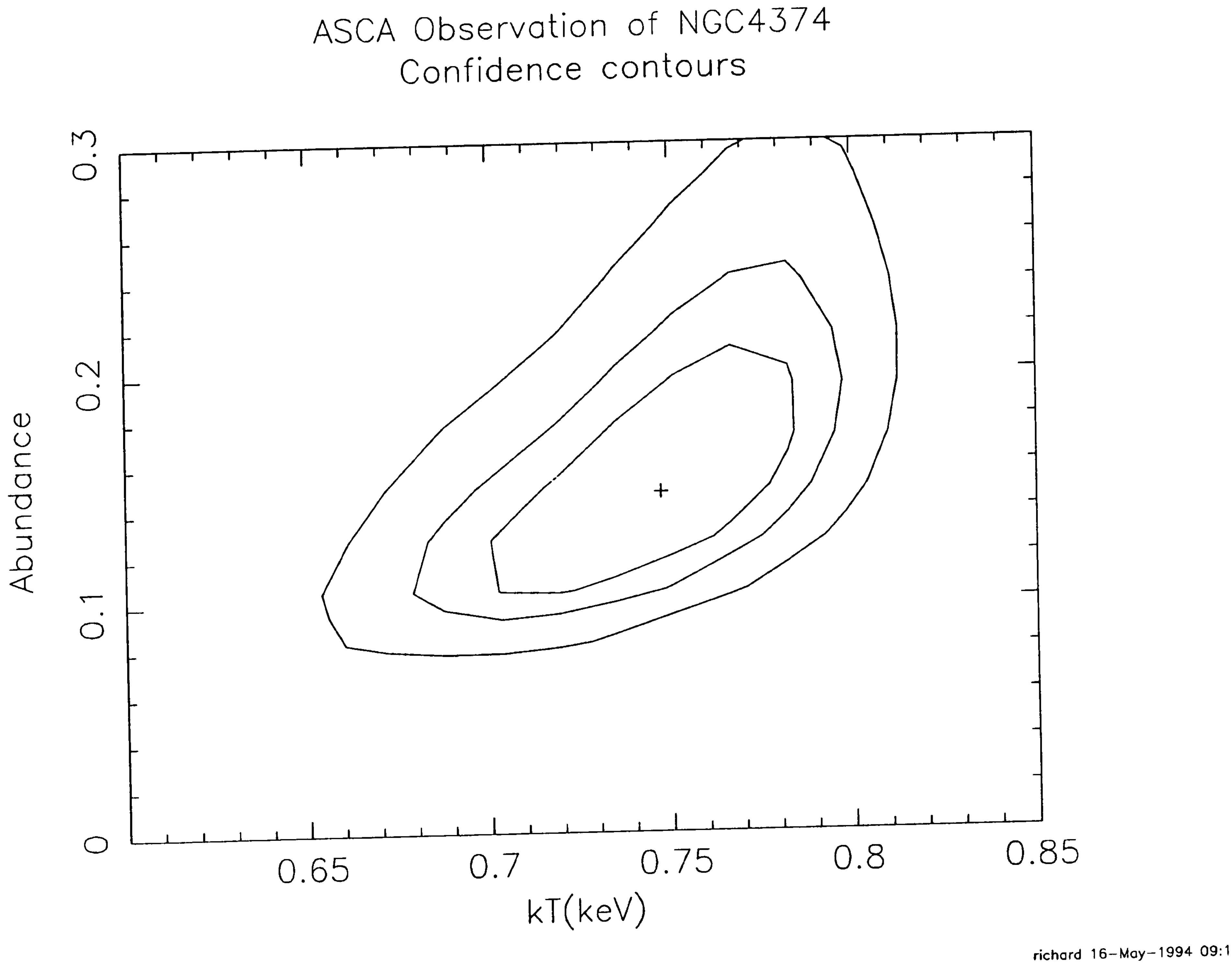

One Temperature Fit to NGC1404
Confidence contours
Abundance
0
0.1
0.2
0.3
0.65
0.7
0.75
0.8
0.85
kT(keV)
richard 8-Jul-1994 16

FIG. 2B


ASCA Observation of NGC4374
Confidence contours
Abundance
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0.2
0.1
0
0.65
0.7
0.75
0.8
0.85
kT(keV)
richard 16-May-1994 09:1: