Analysis of low surface brightness sources with EPIC

Alberto Leccardi

EPIC background working group meeting

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SOMMARIO

1) Proprietà generali di ammassi e ICM
   Temperatura, massa ed altre osservabili

2) Meccanismi di formazione
   Il raffreddamento del core

3) I profili di temperatura
   EPIC e il problema del fondo
   Incertezze statistiche e sistematiche
   Conclusioni e prospettive future
If background dominates and spectra have few counts

- Apply correct statistic
- Control systematics
The counting process of the number of photons collected by a detector during a time interval is a typical example of a Poisson process.

A spectrum is univocally defined by the observed counts, $O_i$, in each channel.

Given a model, the expected counts, $E_i$, in each channel can be calculated.
The probability, $P$, of obtaining a particular spectrum follows a Poisson distribution and is a function of the model parameters, $\alpha$:

$$P(\alpha) = \prod_{i=1}^{N} \frac{E_i^O(\alpha) \exp(-E_i(\alpha))}{O_i!}$$
Given a measured spectrum, astronomers wish to determine the best set of model parameters. The maximum likelihood method determines the parameters which maximize $P$. One is likely to collect those data which carry the highest chance to be collected.

The Cash (Cash, 1979) and the $\chi^2$ statistics are based on these concepts. The former is more appropriate when analyzing low count spectra.
THE $\chi^2$ STATISTIC

The $\chi^2$ is based on the hypothesis that each spectral bin contains a sufficient number of counts to make the deviations of the observed from the expected counts have a Gaussian distribution.

Table 2. Weighted averages of temperature best fit values compared to the input value and relative differences $\Delta T/T_0$, using different channel groupings.

<table>
<thead>
<tr>
<th>$N_{\text{bin}}$</th>
<th>$kT_0$</th>
<th>$kT$</th>
<th>$\Delta T/T_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>7.00</td>
<td>6.99±0.01</td>
<td>-0.1%</td>
</tr>
<tr>
<td>100</td>
<td>7.00</td>
<td>6.95±0.01</td>
<td>-0.7%</td>
</tr>
<tr>
<td>25</td>
<td>7.00</td>
<td>6.89±0.01</td>
<td>-1.6%</td>
</tr>
</tbody>
</table>

Notes:  
\(^a\) counts per bin;  
\(^b\) input temperature in keV;  
\(^c\) measured temperature in keV;  
\(^d\) relative difference.
THE $\chi^2$ STATISTIC

This hypothesis is satisfied only for **very large** counts per bin.

Every kind of channel grouping implies **loss** of spectral **information**.

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**Table 2.** Weighted averages of temperature best fit values compared to the input value and relative differences $\Delta T/T_0$, using different channel groupings.

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Notes: $^a$ counts per bin; $^b$ input temperature in keV; $^c$ measured temperature in keV; $^d$ relative difference.
The Cash and the $\chi^2$ statistics are based on maximum likelihood methods.

From the literature (e.g. Eadie 1971) it is well known that:

**ML estimators** could be **biased** especially in the case of highly **non linear model** parameters (e.g. $kT$ of a bremsstrahlung model)

Bias: difference between expected and true value
THERMAL SOURCE ONLY CASE

Table 1. Weighted averages of temperature best fit values compared to the input value and relative differences $\Delta T/T_0$, using different exposure times and statistics.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$kT_0$</th>
<th>$kT$</th>
<th>$\Delta T/T_0$</th>
<th>$kT$</th>
<th>$\Delta T/T_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>7.00</td>
<td>6.89±0.01</td>
<td>-1.6%</td>
<td>7.00±0.01</td>
<td>+0.0%</td>
</tr>
<tr>
<td>100</td>
<td>7.00</td>
<td>6.83±0.01</td>
<td>-2.4%</td>
<td>7.03±0.01</td>
<td>+0.4%</td>
</tr>
<tr>
<td>10</td>
<td>7.00</td>
<td>6.76±0.03</td>
<td>-3.4%</td>
<td>6.91±0.02</td>
<td>-1.3%</td>
</tr>
<tr>
<td>5</td>
<td>7.00</td>
<td>6.59±0.04</td>
<td>-5.9%</td>
<td>6.81±0.03</td>
<td>-2.7%</td>
</tr>
</tbody>
</table>

Notes: $^a$ exposure time in kiloseconds; $^b$ input temperature in keV; $^c$ measured temperature in keV; $^d$ relative difference.

Bias appears for low count spectra
The Cash estimator is asymptotically unbiased
## COMPARISON - $\chi^2$ vs. CASH

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$</th>
<th>Cash</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distribution</strong></td>
<td>Gaussian</td>
<td>Poisson</td>
</tr>
<tr>
<td><strong>Channel grouping</strong></td>
<td>Often required (binned data)</td>
<td>Not necessary (unbinned data)</td>
</tr>
<tr>
<td><strong>Goodness of fit</strong></td>
<td>Easy to evaluate</td>
<td>Montecarlo simulation</td>
</tr>
<tr>
<td><strong>Validity</strong></td>
<td>Approximation for large counts</td>
<td>Works also for few counts</td>
</tr>
<tr>
<td><strong>Diffusion</strong></td>
<td>Large</td>
<td>Scarce</td>
</tr>
</tbody>
</table>
INTRODUCING A BACKGROUND

When using the Cash statistic the background has to be modeled (Cash, 1979)

<table>
<thead>
<tr>
<th>Ring</th>
<th>Exp.</th>
<th>( kT_0 )</th>
<th>( kT )</th>
<th>( \Delta T/T_0 )</th>
<th>( kT )</th>
<th>( \Delta T/T_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0'-1.5'</td>
<td>100</td>
<td>5.00</td>
<td>4.84±0.01</td>
<td>-3.2%</td>
<td>4.96±0.01</td>
<td>-0.8%</td>
</tr>
<tr>
<td>1.0'-1.5'</td>
<td>100</td>
<td>7.00</td>
<td>6.78±0.02</td>
<td>-3.1%</td>
<td>6.97±0.02</td>
<td>-0.4%</td>
</tr>
<tr>
<td>1.0'-1.5'</td>
<td>100</td>
<td>9.00</td>
<td>8.69±0.02</td>
<td>-3.4%</td>
<td>8.97±0.03</td>
<td>-0.3%</td>
</tr>
<tr>
<td>1.0'-1.5'</td>
<td>10</td>
<td>5.00</td>
<td>4.81±0.03</td>
<td>-3.8%</td>
<td>4.82±0.03</td>
<td>-3.6%</td>
</tr>
<tr>
<td>1.0'-1.5'</td>
<td>10</td>
<td>7.00</td>
<td>6.78±0.05</td>
<td>-3.1%</td>
<td>6.79±0.05</td>
<td>-3.0%</td>
</tr>
<tr>
<td>1.0'-1.5'</td>
<td>10</td>
<td>9.00</td>
<td>8.68±0.11</td>
<td>-3.6%</td>
<td>8.62±0.08</td>
<td>-4.2%</td>
</tr>
<tr>
<td>4.5'-6.0'</td>
<td>100</td>
<td>5.00</td>
<td>3.95±0.01</td>
<td>-21.0%</td>
<td>4.71±0.02</td>
<td>-5.8%</td>
</tr>
<tr>
<td>4.5'-6.0'</td>
<td>100</td>
<td>7.00</td>
<td>5.24±0.02</td>
<td>-25.1%</td>
<td>6.44±0.03</td>
<td>-8.0%</td>
</tr>
<tr>
<td>4.5'-6.0'</td>
<td>100</td>
<td>9.00</td>
<td>6.43±0.02</td>
<td>-28.6%</td>
<td>8.10±0.04</td>
<td>-10.0%</td>
</tr>
<tr>
<td>4.5'-6.0'</td>
<td>10</td>
<td>5.00</td>
<td>3.02±0.03</td>
<td>-39.6%</td>
<td>3.20±0.03</td>
<td>-36.0%</td>
</tr>
<tr>
<td>4.5'-6.0'</td>
<td>10</td>
<td>7.00</td>
<td>3.68±0.04</td>
<td>-47.4%</td>
<td>3.77±0.04</td>
<td>-46.1%</td>
</tr>
<tr>
<td>4.5'-6.0'</td>
<td>10</td>
<td>9.00</td>
<td>4.11±0.05</td>
<td>-54.3%</td>
<td>4.50±0.06</td>
<td>-50.0%</td>
</tr>
</tbody>
</table>

The bias depends on:
1) the background contribution
2) the spectrum total number of counts
WORK IN PROGRESS...

For the realistic case
no definitive solution has been found

Quick and dirty solution: the triplet method
Correct the posterior probability density functions
(Leccardi & Molendi, 2007 A&A submitted)

Long term solution: ?
Find different estimators (e.g. 1/kT, log(kT), ...)
Explore the Bayesian approach
If background dominates and spectra have few counts

Apply correct statistic

Control systematics
SYSTEMATIC UNCERTAINTIES

Imperfect MOS-pn cross-calibration

Defective background knowledge

The energy band is very important
SYSTEMATIC UNCERTAINTIES

Measuring the temperature of hot GC
Using the energy band beyond 2 keV

✓ Cross-calibration is relatively good
✓ Internal background continuum is well described by a power law
✓ Al and Si fluorescence lines are excluded
✓ Local X-ray background is negligible
I. Internal background: continuum and lines

II. (Quiescent) soft protons

III. Cosmic X-ray background
INTERNAL BACKGROUND

High energy particle induced background beyond 2 keV

Counts sec\(^{-1}\) keV\(^{-1}\)

Energy (keV)

Ni Ka
Cu Ka
Zn Ka
Cu Kb
Zn Kb
Au La
Au Lb

Cr Ka
Mn Ka
Fe Ka
INTERNAL BKG: CONTINUUM

When analyzing different observations we found typical variations of 15% for PL normalization and negligible variations for PL index.

PL index is \(~0.23\) for MOS and \(~0.33\) for pn. It does not show spatial variations.

MOS: SB is roughly constant over all detector.

pn: SB presents a hole due to electronic board, inside the hole the continuum is more intense.
When analyzing different observations we found typical variations of the norm of the lines of the same order of the associated statistical error.
THE R PARAMETER

\[ R = \frac{c r_{IN}}{c r_{OUT}} \]

R depends only on the selected inner region and on the instrument.
R is independent of the particular observation.

R is roughly equal to the area ratio for MOS, not for pn.

Once measured the PL normalization out of the FOV, this **scale factor** allows to estimate rather precisely the PL normalization in the selected region of the FOV for every observation.
SOFT PROTONS

I. Light curve in a hard band (beyond 10 keV) and GTI filtering with a semi-fixed threshold

II. Light curve in a soft band (2-5 keV) and GTI filtering with a 3 σ threshold

III. IN/OUT ratio to evaluate the contribution of quiescent soft protons

Caveat!

Extended sources which fill the whole FOV and emit beyond 5-6 keV
SOFT PROTONS

Goal:
estimate QSP contribution for MOS spectra

Stack many blank field observations (~1.5 Ms)

Use the Cash statistic → Background modeling

Model the total spectrum
CXB + QSP + Int. bkg continuum + Int. Bkg lines
with
PL + PL/b + PL/b + (several) GA/b
Int. bkg continuum is fixed
- PL index from CLOSED
- PL norm = R*norm\textsubscript{OUT}

Int. bkg line norm is free

QSP and CXB parameters are free

We measure both CXB and QSP components
**SOFT PROTONS & COSMIC BKG**

**Work in progress**

Soft proton index is poorly constrained, conversely the normalization uncertainty is 15%

CXB uncertainties are rather large because we are modeling 3 components

<table>
<thead>
<tr>
<th></th>
<th>Index</th>
<th>Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>QSPa</td>
<td>1.4±0.4</td>
<td>6.2±0.9 @ 7.5 keV</td>
</tr>
<tr>
<td>CXBa</td>
<td>1.47±0.07</td>
<td>2.3±0.2 @ 3 keV *</td>
</tr>
<tr>
<td>CXBb</td>
<td>1.52±0.04</td>
<td>2.68±0.03 @ 3 keV *</td>
</tr>
<tr>
<td>CXBc</td>
<td>1.41±0.06</td>
<td>2.46±0.09 @ 3 keV *</td>
</tr>
</tbody>
</table>

* CXB norm is expressed in photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\)
We eliminate QSP component and fit the same data only with CXB and int. bkg.

The index is substantially unchanged, norm increases by 15% due to QSP not to real CXB, uncertainties are strongly reduced.

<table>
<thead>
<tr>
<th>Component</th>
<th>Index</th>
<th>Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>QSP(^a)</td>
<td>1.4±0.4</td>
<td>6.2±0.9 @ 7.5 keV</td>
</tr>
<tr>
<td>CXB(^a)</td>
<td>1.47±0.07</td>
<td>2.3±0.2 @ 3 keV *</td>
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<tr>
<td>CXB(^b)</td>
<td>1.52±0.04</td>
<td>2.68±0.03 @ 3 keV *</td>
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<tr>
<td>CXB(^c)</td>
<td>1.41±0.06</td>
<td>2.46±0.09 @ 3 keV *</td>
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* CXB norm is expressed in photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) keV\(^{-1}\)
De Luca & Molendi have used renormalized background subtraction.

Results are consistent, the difference could be due to the cosmic variance (~7%).

We can infer that also this result could be biased by 10-15% and the uncertainties could be too small.

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* CXB norm is expressed in photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$
Goal:
measure temperature profiles of hot intermediate redshift galaxy clusters

Intermediate redshift $0.092 < z < 0.291$
High temperature $kT > 4$ keV
OUR TECHNIQUE

Galaxy clusters are extended sources. They fill the FOV (intermediate redshift) but in outer regions thermal emission is very small, therefore IN/OUT technique is reliable.

They are hot $\rightarrow$ exponential cutoff at high energies, therefore we use the energy band beyond 2 keV.

We use the Cash statistic (more suitable than $\chi^2$). Cash statistic requires background modeling.
We consider an external ring (10’-12’ in FOV) to estimate the norm of CXB and int. bkg

GC is fixed (iterative estimate)

Int. bkg and CXB: index fixed norm free

QSP is excluded:
- degeneracy
- int. bkg and CXB contain also information on QSP
We rescale so called CXB and int. bkg norm to the inner regions using area ratio.

In the inner regions CXB and int. bkg norm are semi-fixed: they are allowed to vary in a small range around the rescaled values.

Montecarlo simulations tell us how important is the systematic introduced. We found a bias of ~5-10% in the ring 5’-7’ where the background dominates.
If we find a tight relation between the IN/OUT ratio and the QSP normalization, we could model and fix the bulk of QSP component.

This could reduce the bias of 5-10%.

We will implement simulations to evaluate which is the best procedure and to quantify the intensity of introduced bias.