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# Prospects for X-ray Observations of SFRs and young clusters with Chandra and Newton

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**Abstract.** The study of the process of star formation is one of the current frontiers of astronomical research and it will be the subject of many approved Chandra and Newton observations that in the coming few years are expected to shed light on a number of open questions in the field. After considering some of these questions I will show and comment on the in-flight performances of Chandra and Newton and on their impact on selected scientific topics on SFR and young cluster science.

## 1. Introduction

The successful launch of Chandra and XMM-Newton, the two "big" X-ray observatories of the coming decade, has moved the X-ray astronomy in an era of fecund maturity. The capabilities of these observatories in terms of angular resolution, spectral diagnostic and exploration of the Universe at far distances are comparable and in some cases better than those available in other observational domains. X-ray astronomy is now one of the key spectral windows of modern multi-wavelengths astronomical research. Star forming regions (SFRs) are not an exception, as a relevant part of the involved physical processes are affected by high-energy radiations (cf. Montmerle 2000) that conveys crucial information in the Chandra and XMM-Newton observational window.

In the following after considering the approved program of Chandra and XMM-Newton observations of SFRs and young stellar clusters (the separation between the two groups occurring in a fuzzy way around 30-50 Myrs), I will present some of the key problems that will be addressed by the new data, as well as early results obtained with Chandra, and I will comment on the present performances (June 2000) of XMM-Newton and on their impact on the SFRs observation program.

## 2. Chandra and XMM-Newton Early Observational Programs

In order to gain an insight on the scientific questions that Chandra and XMM-Newton will address I have searched the approved programs for observations of SFRs and young stellar clusters. The result of this search (cf. Tables 1 and 2) reveals that both Chandra and XMM-Newtow will devote a substantial amount of early observational programs to these subjects, with emphasis on SFRs.

Table 1. SFRs and young stellar clusters in the Chandra AO1 Garantie Time Observation (GTO) and Guest Observation (GO) and AO2 GTO programs (June 2000)

| Target Name | Instrument | Exp. Time |
|---|---|---|
| NGC 1333 | ACIS-I | 50 ks |
| IC 348 | ACIS-I | 50 ks |
| Orion Trapezium Region | ACIS-I | 50 ks |
| Orion Trapezium Region | HRC-I | 69 ks |
| Orion region | ACIS-I | several obs |
| CrA Cloud Core | ACIS-I | 20 ks |
| rho Oph | ACIS-I | mosaic of 6 x 5 ks |
| rho Oph | ACIS-I | 2 x 100 ks |
| NGC2516 | ACIS-I | 20 ks |
| NGC2516 | ACIS-S | 20 ks |
| NGC2516 | HRC-I | 20 ks + 50 ks |
| M16 | ACIS-I | 80 ks |
| NGC 6530 | ACIS-I | 61 ks |
| W3B | ACIS-I | 40 ks |
| HH1 | ACIS-S | 20 ks |

The vast majority of these observations are planned with CCD imaging detectors, ACIS on Chandra and EPIC on XMM-Newton, characterized by a wide field-of-view and by a spectral resolution of $\sim$ 150 eV, few observations at very high angular resolution are planned with the Chandra HRC and only a handful of PMS stars will be targets of high spectral resolution observations (see sect. 6). For the imaging observations summarized in Tables 1 and 2 I have listed the target name, and the approved exposure time and for the case of Chandra the detector of choice. The exposure time allows deriving an estimate of the limiting sensitivity according to the known in-flight performance (cf. Figure 2).

## 3. Key Objectives of Imaging Surveys

Without any claim of completeness (for a more extensive discussion on open issues on X-ray emission from SFRs cf. Feigelson & Montmerle 1999) the overall approved programs will clearly allow:

- Investigating coronal activity of young very low-mass stars, in particular to search for magnetic activity below the hydrogen burning limit.

- Obtaining a more complete census of PMS stars in early evolutionary phases that could be hardly found at other wavelengths (young stars are intense coronal emitter) in order to improve the determination of Initial Mass Functions (IMF).

Table 2. SFRs and young stellar clusters in the XMM-Newton EPIC GTO and AO1 GO program (June 2000). Only observations in priority A or B have been considered.

| Target Name | Exposure Time | Target Name | Exposure Time |
|---|---|---|---|
| NGC 2024 | 45 ks + 25 ks | L1448-C | 30 ks |
| NGC 2023 | 25 ks | NGC 1333 | 50 ks |
| IC 2602 | 45 ks | Orion P1795 | 20 ks |
| IC 2391 | 45 ks | OMC2/3 | 100 ks |
| alpha Per | 50 ks | L1641-N | 50 ks |
| Upper Sco-Cen | 2 x 50 ks | NGC 2264 | 2x35 ks |
| R CRA | 20 ks | Chamaeleon | 28 ks |
| rho Oph | 25 ks + 50 ks | Serpens | 50 ks |
| IC 348 | 40 ks | NGC 2362 | 50 ks |
| L1551 | 50 ks | NGC 2547 | 50 ks |
| Blanco 1 | 50 ks | Pleiades | 2 x 50 ks |

- Searching for correlation between coronal activity and rotation to probe the early evolution of magnetic activity for fully convective stars, and for stars in the lower part of Hayashi track which are developing radiative cores.

- Studying, thanks to the long ($\geq$ 30 hours) uninterrupted observations, the incidence and the properties of X-ray flares, as well as of less extreme X-ray variability of CTTS and WTTS (e.g. related to rotational modulation).

- Monitoring the X-ray, UV and optical variability of CTTS to investigate if the X-ray emission is related to the post-shock gas close to the stellar surface or to the region coupling the inner disk to the stellar magnetic field.

- Searching for hard X-ray emission from Class I (and even Class 0) protostars, in order to augment/improve previous ASCA positions and luminosities. It will be possible to obtain high S/N X-ray CCD spectra to look for hard X-ray emission, and to derive/constrain a model description of the emitting plasma. The high spatial resolution of the new X-ray image will allow a secure identification with the IR counterparts.

- Investigating the nature/origin of X-ray emission from Herbig Ae/Be stars, in order to distinguish among emission from shock processes and wind-fed magnetospheres (characterized by emission $<$ 1 keV), or coronal models in which hotter plasma is expected, or even the case that the emission is originated from an unseen T Tauri companion(s).

- Discovering new star formation regions that should exist in the solar vicinity if the proposed Gould Disk scenario is correct.

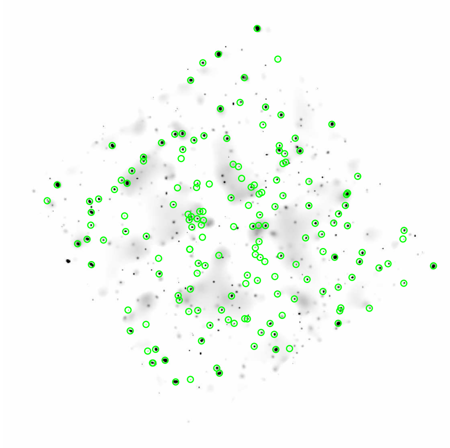

Figure 1. Chandra ACIS-I 20 ks image of the young open cluster NGC 2516. In order to improve its apparency the original image has been smoothed. The circles identify the sources found with the Pwdetect algorithm.

## 4. Chandra Performances and Some Early Results

Since the approved program clearly reflects the predicted pre-flight Chandra capabilities, it is worth to illustrate with the results of the analysis of Performance Verification (PV) and some early GTO data what are the real *after launch* performances.

Chandra has been launched in July 1999 and has started to collect data about one month later. In the early phase of the mission an unpredicted flux of soft protons almost "focused" by the mirrors[1] has degradated the charge transfer efficiency of the front illuminated (FI) CCDs of the ACIS-I and ACIS-S detectors. This degradation, that with a prompt adjustment of mission operations has been stopped since October 1999, has produced a spatial-dependent reduction of the energy resolution, that is almost at the nominal value (i.e. $\sim 150$ eV) for pixels near reading nodes and reduced by a factor up to 3 for the pixels far from reading nodes. Provisions to recover (most of) the original spectral resolution are still under investigations, and some are routinely applied since end January 2000. The Chandra superb imaging capability has not been affected and is well within the pre-flight expectation, in the center of field-of-view a resolution of about $\sim 0.3$ arcsec is achieved, thanks also to the extremely good aspect reconstruction. As an effect of the unexpected soft proton flux image background is higher than pre-flight expectations, with episodes of very intense background (up to a factor 10-50) observed from time to time. Taking advantage of entire information produced by detectors the instrument teams have been

[1]The process involved is not strictly speaking a reflection, but indeed it has been suggested that it can be explained by a scattering interaction between atoms of the mirror surface and incident protons with energy below 0.5 MeV (Aschenbach 2000). If this explanation is correct the scattering angles is predicted to be within $1^\circ$ of the angle for a true reflection.

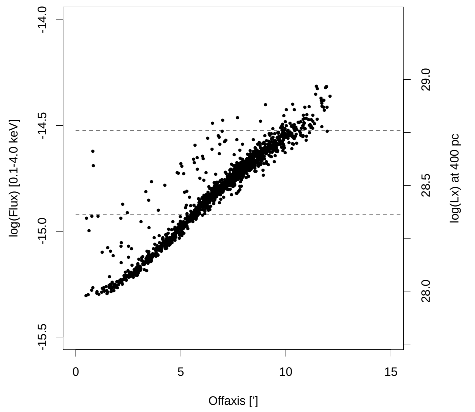


Figure 2. Sensitivity expressed in terms of X-ray flux and luminosity in the 0.1-4.0 keV bandpass that will be reached in a 100 ks Chandra ACIS-I observation for sources whose emission can be described with a thermal spectrum with T=0.3 keV and a hydrogen column $N_H = 3\ 10^{20}$ $cm^{-2}$, i.e. for a conversion factor of 7.9 $10^{-12}$ erg $cm^{-2}$. Values have been scaled from measurements on real data. The bottom envelope defines the attainable limiting sensitivity, the scatter of data point is due to the presence of sources at various places in the fov.

able to develop post-facto procedures that screen out most of the additional background. As a result of those efforts a typical increase of a factor $\sim 2$ in the background with respect to pre-flight expectation is currently achieved. Since the typical increase in the background level is small, and thanks to Chandra superb angular resolution, essentially all observations of point sources fall in the so-called photon limited regime (the limiting sensitivity scales linearly with the exposure time) with (small) departures becoming appreciable only for exposure time greater than 500 ks. Chandra is a terrific observatory for deep imaging of crowded fields, like those of SFRs! This has been clearly shown by the analysis of the PV data of the young open cluster NGC 2516 (cf. Flaccomio et al. 2000a, Harnden et al. 2000a, Wolk et al. 2000, and Figure 1), where two "shallow" 20 ks ACIS-I and HRC-I observations have allowed to reach, thanks also to Pwdetect, a very effective wavelet detection code developed at OAPA (Damiani et al. 2000), the limiting sensitivity of $\sim 3\ 10^{-15}$ erg/sec/cm$^2$. Scaling those results one can predict the expected limiting sensitivity (as a function of off-axis angles) for a 100 ks ACIS-I observation (cf. Figure 2): limiting sensitivities much better than $10^{-15}$ erg/sec/cm$^2$ can clearly be reached.

In order to elucidate these deep imaging capabilies let us consider the problem of assessing the coronal emission level of very-low mass and brown dwarf young stars. Neuhäuser et al. (1999) have reported the X-ray detection of a few brown dwarfs with log ($L_X/L_{Bol}$) in the -3 – -4 range. Given the size of the sample the generality of these findings and the determination of the age at which ($L_X/L_{Bol}$) rapidly declines are still open issues. The Pleiades data show that low-mass stars are in the so-called saturated regime with $\log(L_X/L_{Bol}) \sim$ -3.3 (Stauffer et al. 1994, Micela et al. 1996, 1999), similar $\log(L_X/L_{Bol})$ values

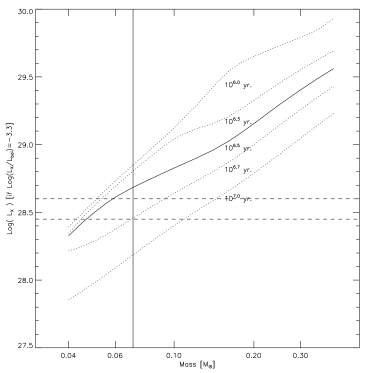


Figure 3. The predicted $L_X$ behaviour as a function of stellar mass for a coronal emission occurring at the saturated level, $\log(L_X/L_{Bol}) =$ -3.3. The five oblique lines are computed, starting from the D'Antona & Mazzitelli (1997) tracks, for 5 different stellar ages in the 1-10 Myr range. The vertical line marks the brown dwarf limit. The top horizontal dashed line indicates the typical limiting sensitivity for a 100 ks Chandra ACIS-I observation at a distance of $\sim$ 750 pc for the central $\sim$ 6'x6' region, the bottom line indicates the deepest reachable limiting sensitivity. Young PMS low-mass stars and brown dwarfs with X-ray luminosity above those lines will be detected.

have been found for the NGC 2264 members (Flaccomio et al. 2000b), but with the saturation starting at larger masses.

Assuming that all young very-low mass and brown dwarf stars emit at the saturated level we can predict (cf. Figure 3) the expected $L_X$ as a function of age and mass and explore the region of the parameter space made accessible by Chandra deep images. An inspection of Figure 3 reveals that the brown dwarfs can be detected, if they emit within 1 dex of the saturated level, in **all** the nearby SFRs and young open clusters. Since the superb Chandra angular resolution prevents ambiguity in the identification process, we will soon have a direct test of the above question.

As a final examples let us concentrate on the recent Chandra observations of the Orion Trapezium region obtained with ACIS-I and HRC-I. Both observations are part of the Chandra GTO program of G. Garmire and S. Murray, respectively. The 48 ks ACIS-I observation is being analyzed by a group led by Penn-State University (Garmire et al. 2000, cf. also Hillenbrand 2000). The 63 ks HRC-I observations (cf. Figure 4), obtained few months after the ACIS-I one, is being analyzed jointly by scientists at SAO and OAPA. Both observations are astonishing for the number of individual detected sources, Garmire et al. (2000) report the detection of 973 individual sources, and more than 700 sources have been found with Pwdetect on the HRC-I data (cf. Harnden et al. 2000b). The vast majority of those sources have as counterparts young PMS stars belonging to the Orion Nebula Cluster (ONC), one of the densest PMS stellar cluster known with $\sim$ 2000 members in a sphere of 1 pc radius (i.e. in 8', cf. Hillenbrand 1997). These observations are providing the largest sample

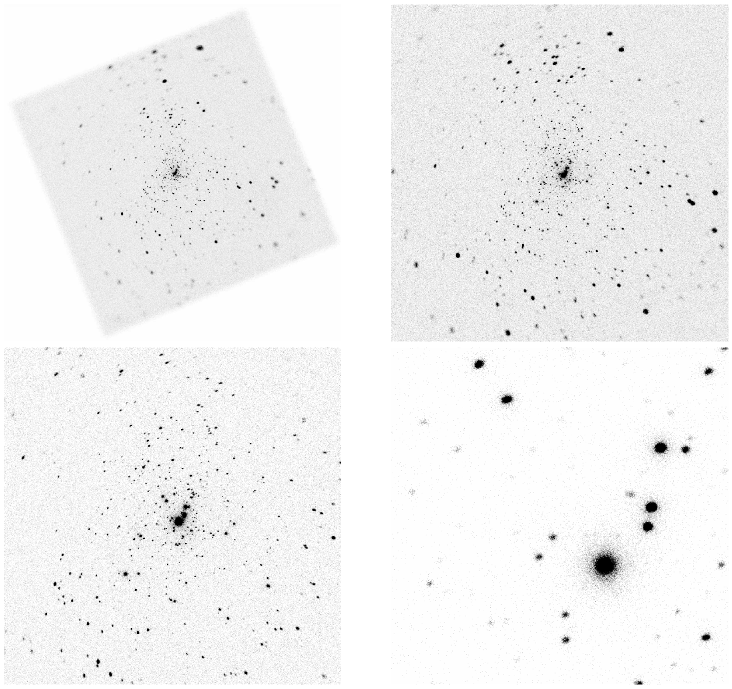

Figure 4. The panels show 63 ks Chandra HRC-I images of the Orion Nebula Cluster region at four different pixel sizes: (top left) the entire $30' \times 30'$ surveyed region at 4" pixel, (top right) the central 17'x17' arcmin region at 2" pixel, (bottom left) the central 8'.5x8'.5 region at 1" pixel, (bottom right) the Trapezium region at full resolution, i.e. 0".0125.

of PMS stars homogeneously studied in X-ray so far and will allow answering to open questions on the complex relationships between PMS X-ray emission and stellar age, mass, radius and rotation. The Chandra imaging surveys of ONC region allow reaching a limiting sensitivity of $\sim 10^{-15}$ erg/sec/cm$^2$, i.e. about a factor 20-30 times deeper than previous ROSAT surveys.

The above examples should make it clear the terrific possibilities opened by Chandra deep imaging. It is a simple exercise to scale the results I have shown or mentioned to the observations listed in Table 1, to be pleased by the attainable limiting sensitivity with respect to ROSAT or ASCA, by the so exquisite quality of imaging to make the follow-up identification trivial, once one has deep enough optical or IR images.

## 5. XMM-Newton EPIC Performances and the SFRs Program

XMM-Newton has been launched at the very end of 1999 and it started to collect data in February 2000. The mission is still in its calibration/verification phase and no observations of SFRs have been performed. In the following I will concentrate on the performance of EPIC, on which, as Co-I, I am more directly involved. In summary, the early observations have shown that XMM-Newton PSF is within the pre-flight expectations, and that the energy resolution for both

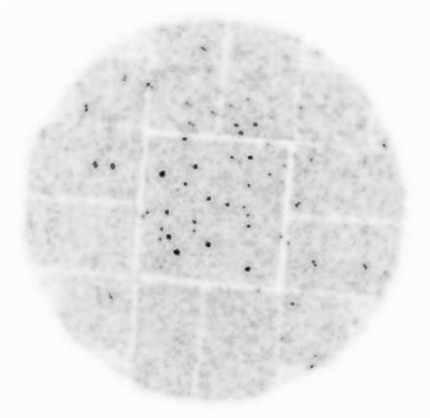

Figure 5. XMM-Newton EPIC/MOS 20 ks calibration image of the young open cluster NGC 2516. In order to improve its apparency the image has been smoothed (adapted from original image at http://spdext.estec.esa.nl/home/xmm-newton/index.cfm)

MOS and PN cameras is $\sim 150$ eV in very good agreement with expectation, but that the EPIC background level is higher than predicted before launch. Current estimates indicate a background level that, above $\sim 2$ keV, is substantially higher than predicted, while it is within the expectation below $\sim 2$ keV. Episodes of even higher background level have been observed (in analogy with what has been seen with Chandra). Current views explain the high background level as associated both to soft protons "focussed" by the mirrors, whose contribution can be partly screened out, and to events associated to either photons or particles within the EPIC enclosures whose first origin is due to an intense flux of cosmic rays associated to the solar activity near its maximum. If the current understanding is correct there are expectation for a seasonal improvement as the satellite orbit will move in a region where most of the orbit is outside the earth magnetosphere filled with soft protons, and long-term improvement as we move away from solar maximum (Molendi 2000).

The increase of the typical background level together with the size of the XMM-Newton PSF, $\sim$ 12" HPD, has the effect to make the reach of limiting sensitivity below $10^{-14}$ erg/sec/cm$^2$ more time costly than expected (Molendi 2000). In summary, with current performance XMM-Newton will be a very good instrument for spectroscopy studies, and surely better than Chandra thanks to its larger collecting area, but its deep imaging capabilities are much more limited than those of Chandra. The capabilities of EPIC on-board XMM-Newton for the scientific topics we are considering can be illustrated by the image of NGC 2516 (cf. Figure 5) based on early calibration data.

As a result of this recent findings it is clear that Chandra and XMM-Newton observations will be indeed extremely complementary, Chandra will make it possible studies of faint sources even in crowded fields and XMM-Newton detailed spectroscopic studies of sources with flux down to $\sim 10^{-13}$ erg/sec/cm$^2$.

## 6. High Spectral Resolution Observations of PMS Stars

Chandra and XMM-Newton will make it possible to obtain for the first time high resolution spectra (HRS) of very young and PMS stars. Grating spectrographs are photon starved and it will be possible to obtain good quality spectra in a reasonable length exposure time only for sources with flux slightly lower than $\sim 10^{-11}$ erg/sec/cm$^2$. As a result only a handful of PMS stars are in the approved programs, specifically: Orion Trapezium stars (70ks), and TW Hya (50ks) with Chandra HETGS and SU Aur (52ks), HD 283572 (42ks), and V410 Tau (100ks) with XMM-Newton RGS. This latter detector thanks to its larger collecting area will compare favoreably with respect to the grating spectrographs onboard of Chandra. Planned observations will allow investigating the thermal structure, coronal abundances, and density of PMS coronae and their changes with evolutionary stage. In particular HRS will allow deriving "model-independent" description of PMS coronae. It is also conceivable that, thanks to the high energy response ($> 2.5$ keV) of Chandra HETGS, future very long observations will make it possible to study the hard spectrum of few selected PMS stars.

In order to illustrate the capabilities of high resolution observations I have simulated the Chandra HETGS spectrum of HD 283572 in a 100ks observation (cf. Figure 6). It is very simple to unambiguously identify 20 lines, all with $\geq 20$ counts at the peak. The large number of iron lines detected, from Fe XVII to Fe XXIV, can be used to constrain the differential emission-measure (DEM) distribution between $\log T = 6.6$ and 7.5 K. Lines of other elements in different ionization stages (Mg XI and Mg XII, Ne X, Si XIII and Si XIV, OVIII) will also detected, yielding an additional test of ionization balance and DEM distribution, as well as abundance measurements. It is also conceivable that a direct test of the coronal extent can be provided by measurement of the broadening of X-ray lines emitted by a PMS corona, since very broad lines should be emitted by extended (1-2 $R_*$) almost corotating coronae, if they exist around fast rotating PMS stars.

In summary, thanks to Chandra and XMM-Newton in the coming decade we will surely see new revolutionary data and it is easy to predict that those will produce exciting discoveries in the field of SFRs and very young stellar clusters.

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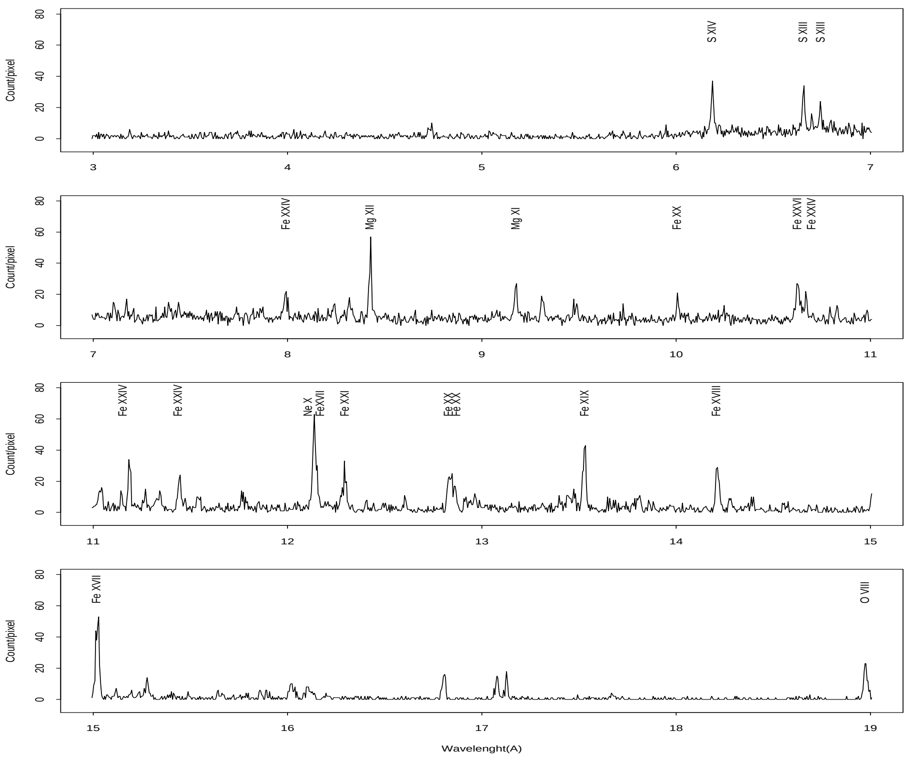


Figure 6. Simulated 100 ks Chandra HETGS spectrum of HD 283572 (+1 and -1 MEG orders summed). Univocally identified emission lines above the 4 $\sigma$ detection threshold are labeled.

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