STAR FORMATION, DISK EVOLUTION AND CORONAL ACTIVITY AT LOW METALLICITY

Abstract

The metal content of gas is thought to have a strong impact on star and planet formation: molecular cloud collapse, dust formation, protostellar interior opacities, and protoplanetary disk evolution. Unfortunately, the low metallicity young clusters that can probe star and planet formation in metal-poor environments are generally located at great distances: in the outer regions of our Galaxy or in the Magellanic Clouds. The one exception identified to date is the relatively nearby young cluster Dolidze 25 ($\sim 4\,kpc$, age 4-6 Myr). It is of especially low metallicity ($Z = 0.17 Z_{\odot}$) and is the best target known for studying metal-poor star and planet formation. A 150 ks *Chandra* ACIS-I observation, complemented by existing deep photometry from optical to $22\,\mu m$, will for the first time probe the low metallicity IMF, protoplanetary disk evolution, and the ionizing coronal X-ray properties of disk-hosting and disk-less stars down to solar masses.

Scientific Rationale

Studying the star formation process in different regions in our Galaxy represents the most direct way of understanding environmental effects on the early evolution of stars, circumstellar disks and planets. *Chandra* studies of different star forming regions have demonstrated the unique power of high spatial resolution X-ray surveys in providing an accurate census of stellar members down to the lowest mass stars. X-ray surveys can penetrate many magnitudes of visible extinction found in embedded regions that heavily bias optical and near-infrared studies.

In the quest to probe diverse star-forming environments, low-metallicity regions, which are of paramount astrophysical importance for understanding how stars and planet form, both in the early Galaxy and at higher redshifts in the earlier Universe, have proved particularly elusive. They are too distant for detailed observations (in the outer Galaxy or in the Magellanic Clouds), and all Galactic star-forming regions studied by Chandra to date are consequently of approximately solar metallicity.

Protoplanetary disks at low metallicity

The lifetime of circumstellar disks in low-metallicity clusters is expected to be shorter than those at higher metallicities. The large gas-to-dust ratio in disks increases their ionization level, resulting in a more efficient coupling between the disk and the stellar magnetic field. In this way, the angular momentum transfer in the disk due to magneto-rotational instability should be more efficient, resulting in higher accretion rates and shorter dissipation times [1]. Besides, photoevaporation of gas and small dust particles is thought more efficient for larger gas to dust ratios, since far-ultraviolet and X-ray radiation can heat the gas more efficiently when the dust opacity is lower [2].

The implication of a lower disk fraction in low metallicity environments is profound: that the planetary formation efficiency varies from the inner to the outer Galaxy, and also that it was lower in the past when the Galaxy was metal-poor. It is also relevant to the finding that the probability of a star hosting a planet increases with stellar metallicity [3].

Very limited attempts to verify a rapid dissipation of circumstellar disks in metal-poor clusters have been done up to now. In low metallicity young clusters in the outer galactic disk (galactocentric distance of $\sim 18\,kpc$), evidence was found of lower disk fractions by a factor of 2 or more than in solar metallicity clusters with similar age [4]. However, this result is by no means definitive, since the photometric criteria used to find stars without disks suffer large contamination by reddened cluster non-members. Besides, different result has been found in the cluster NGC 1893 observed with Chandra and with similar galactocentric distance, where the disk fraction is similar to that of coeval clusters in the vicinity of the Sun [5]. Only X-ray selection criteria ensure a reliable census of Class III (disk-less) objects, and only a target close to the Sun, such as Dolidze25, can provide access to the low mass stars.

Low metallicity IMF

The Initial Mass Function (IMF, the distribution of stellar masses at birth) seems to be remarkably constant across a wide range of star-forming environments in our Galaxy [6]. It is well-described by a power-law with index $\Gamma = 1.35$ above a few solar masses and a log normal or shallower power-law, $\Gamma \sim 0.25$, for less massive stars [7]. The apparent universality of the IMF is of central importance in the physics of star formation and cloud fragmentation, and in the study of the unresolved intermediate- and low-mass stellar content of distant clusters and other galaxies. It is one of the fundamental properties that any theory of star formation must explain.

Since metallicity is thought to affect the mass of the clumps formed by fragmentation of molecular clouds [7], there is an expected relation between the cluster's IMF and gas metallicity. However, recent theoretical simulations of star formation find that feedback of stellar radiation can dominate cloud temperature and fragmentation, leading to only a weak IMF relation with the metallicity of the parental cloud [8]. At present, neither argument is strongly supported by observations, since only the high- and intermediate-mass stellar regime has been properly explored, given the great distances and the large contamination in membership of known low metallicity clusters. X-ray studies of nearby low-metallicity clusters are then crucial to study the independence of the IMF on metallicity and test star formation thereby.

Metallicity and coronal X-ray activity

Low metallicity is expected to affect coronal activity and stellar X-ray emission. This has been observed in the low metallicity $660\,Myrs$ old open cluster NGC 6633, where the X-ray emission level of F-G stars is weaker than in coeval clusters with solar metallicity [10].

The following processes can affect X-ray emission in low-metallicity stars. First, the lower opacity in the stellar interior is expected to shift the onset of magnetic activity seen to occur at F3-F5 stars at solar metallicity to later spectral types. Second, different metallicity results in dif-

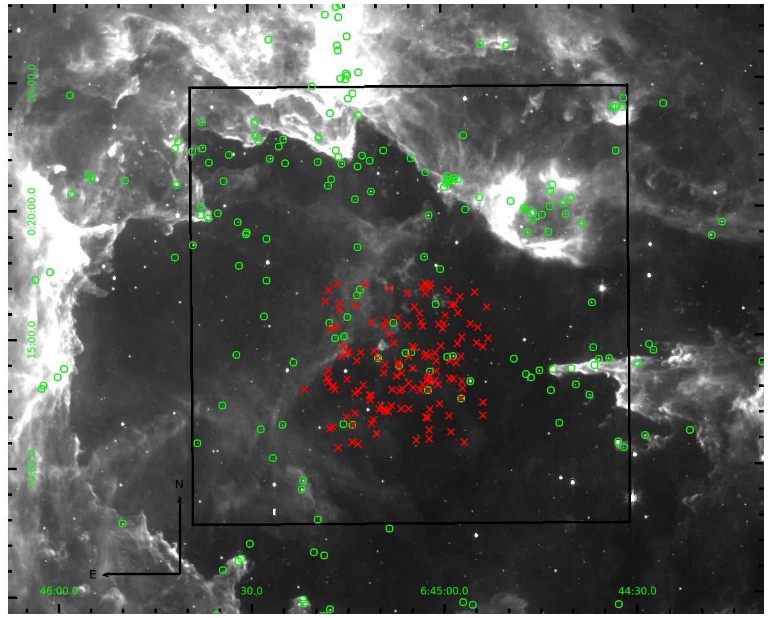

Figure 1: IRAC $8.0\,\mu m$ image of Dolidze 25 and the associated nebulosity. Circles mark the identified ClassI/II objects [14], while crosses mark the identified cluster members in the central region [15]. The box delimits the ACIS-I FoV.

ferent depth of the convective zone, and therefore a different dynamo efficiency. Third, the coronal X-ray emission itself can be affected by metallicity because most of the radiation comes from line emission (bound-bound transitions) in highly ionized metals. Finally, metallicity can affect also stellar rotation, since the angular momentum loss is mostly driven by magnetic braking, and then the level of saturation of the X-ray emission observed in young stars (see, for instance, [11], [12]).

Since coronal X-rays in T Tauri stars provide the dominant source of ionization for protoplanetary disks in the epoch of planet formation [13], it is important to verify whether this result holds in the T-Tauri phase. Detailed studies of the X-ray properties of the stellar population of young low-metallicity clusters that can be easily compared to well-studied young clusters with solar metallicity, will determine if and how metallicity effects coronal X-ray emission.

Objectives

To understand how low metallicity affects the IMF, protoplanetary disk evolution and the coronal activity in young stars, *Chandra* observations of nearby, low metallicity clusters are necessary. We propose a $150\,ks$ *Chandra*/ACIS-I observation of the cluster Dolidze 25, associated with the HII region Sh 2-284 [16], which has low-metallicity ($Z = 0.17Z_\odot$, [17]), young age (4-6 Myrs,[18]), and a distance of only $\sim 4\,$kpc [15]. The low metallicity is expected given the large galactocentric distance [19], and it has been confirmed from spectroscopy of three O members of the cluster. Dolidze 25 is *the* best available target to study star formation, disk evolution and X-ray emission at low metallicity: it has the lowest metallicity among the known young (less than 10 Myrs old) and moderately nearby clusters, and, even if some nebulosity is still present, it has low extinction in the central area ($A_V = 2 - 2.6^m$, [18,20]) which renders observation of the low-mass members easy.

An extensive set of multi-wavelength data on Dolidze 25 already exists, enabling accurate spectral typing and ready identification of the disk-bearing stars: the deepest available data are in RI bands (down to $I \sim 22^m$, $0.4\,M_\odot$) published together with optical spectra available in the $30' \times 30'$ region around the cluster [18]; there are also optical $BVr'i'$ data from the CoRoT EXODATA [21] together with the light curves of 28 members [22], IPHAS $r'i'H\alpha$ data down to $r' \sim 20^m$, $UBVRIJHK$ (down to $V \sim 21^m$ and $J \sim 20^m$) of the central $6' \times 6'$ area corresponding to Dolidze 25, 2MASS JHK data, Spitzer/IRAC data down to $[3.6] \sim 18^m$ [14] in a field $0^\circ.95 \times 1^\circ.3$ centered on the cluster, and recent observations with WISE in four bands from $3.4\,\mu m$ to $22\,\mu m$.

[18] found that stars in the central cluster are younger than $10\,Myrs$, with a small age spread, but [15] proposed the presence of an older population of stars in the cluster about $\sim 40\,Myrs$ old. There is evidence of sequential star formation activity in this region, triggered by the massive stars in Dolidze 25. Star formation is ongoing in the molecular cloud surrounding the cluster, with small sites of star-formation younger than $1\,Myr$. In fact, the parental cloud is rich in Class I and Class II objects (137 in the field that we will observe with Chandra) [14]. Based on this selection of disk-bearing members, a low disk frequency has been reported [18], but the selection method for disk-less stars is compromised by the limitations of optical photometric criteria. The combination of X-ray data with this extensive set of optical+infrared data will allow us to find conclusive results on the disks frequency and age of the cluster, to verify the presence of the older $40\,Myrs$ old population and eventually to easily distinguish it from the younger members, given the sepratation of the two isochrones in the diagrams and the almost uniform and low reddening in the central area.

Our aim is to complete the cluster membership by finding both the disk and disk-less X-ray sources, in order to derive the IMF and the disk frequency of the cluster and to compare them with those of other young clusters with solar metallicity. We will identify with about 100% completeness all stars of the cluster down to $1\,M_\odot$, which is the limit of existing disk selection. We will determine stellar masses and the IMF using stellar evolution models compared with optical and NIR photometric indices. We will find the disk frequency and compare it to that of solar-metallicity clusters. Based on the disk frequency for clusters with similar age and solar metallicity [23] and previous estimates for the disk frequency of the cluster [18], we expect more than 600 cluster disk-less members. Combined with the 137 stars found with disks falling in the ACIS field [14], we estimate that we will determine the disk frequency with a precision of about 5%, enabling accurate comparison with other clusters. We will also study the spatial variation fo disk frequency, to analyze the role of O stars in triggering the star formation in the molecular cloud.

The proposed $150\,ks$ observation will also yield the X-ray luminosity function (XLF) and X-ray properties of the cluster members down to $1\,M_\odot$. The XLF will be compared to those of other young clusters with solar metallicity in order to understand whether the sub-solar metallicity affects the coronal emission of the cluster members and the temperature of the emitting plasma. Besides, the knowledge of the fractional X-ray luminosity of selected members will allow us to verify whether saturation of X-ray emission in pre-Main Sequence stars is affected by low metallicity.

Figure 1 shows the IRAC [8.0] image of Dolidze 25, with the positions of the existing known ClassI/II sources and the known members in the center of the cluster [15]. With the requested *Chandra* observation, pointed at $\alpha = 06:45:05$ and $\delta = 00:16:15$, we will observe the central cluster almost on-axis and both the pillar in the West and the dense nebulosity in the North, with evidence of ongoing star formation.

Feasibility

To reach our goals, we need an exposure time of $150\,ks$, necessary to be 100% complete at about $1\,M_{\odot}$ as calculated in the following way. The Orion Nebula Cluster is the only cluster where all members have been observed in X-ray down to $0.1\,M_{\odot}$ in the Chandra Orion Ultradeep Project (COUP, [24]). In COUP data, the lowest L_X for Orion members in the $0.9\,M_{\odot} - 1.1\,M_{\odot}$ mass bin is $7.2 \times 10^{29}\,cm^2 \cdot s^{-1}$, corresponding to a flux of $3.76 \times 10^{-16}\,erg \cdot s^{-1} \cdot cm^{-2}$ for stars at $4\,kpc$. Using PIMMS v.4.5, this flux corresponds to $4.78 \times 10^{-5}\,cnt/sec$, assuming a typical Raymond-Smith thermal emission spectrum with $kT = 1.37\,keV$ and $N_H = 6.7 \times 10^{21}\,cm^{-2}$ (derived from the HEASARC nH web tool). This corresponds to 7 photons observed in $150\,ksec$, which, by our own experience and given the expected low background, ensures the observability of the faintest $1\,M_{\odot}$ cluster members by using PWDetect [25] and CIAO wavdetect tasks [26]. With the same approach, we verified that our sample will be with good probability complete down to $0.7\,M_{\odot}$. To convert fluxes into luminosities, we used the must recent distance estimate of $4\,kpc$ (actually the estimate ranges from $3.6\,kpc$ to $4\,kpc$). In the past, larger distances have been estimated for Dolidze 25, up to $6\,kpc$. In the most pessimistic estimate of cluster distance, we will observe from the faintest $1\,M_{\odot}$ cluster member 3 photons in $150\,ksec$, which is still enough to have good chances of source detection with PWDetect and CIAO.

With $150\,ks$, we will detect a median of 42 photons from $1\,M_{\odot}$ stars (estimated with the method described above), which are enough to obtain with good statistics the X-ray luminosity and the plasma temperature by the analysis of photon energy quantiles [27] together with spectral fitting for brighter stars. Photon extraction, background estimation and spectral fitting will be performed with the IDL ACIS Extract (AE) package [28].

1 References

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