STAR FORMATION CLOSE TO THE MOST MASSIVE STARS IN OUR GALAXY: UNVEILING THE PMS MEMBERS OF PISMIS 11

Abstract: Star and planet formation in massive clusters happens under the intense UV-FUV radiation from high mass stars. The effects of UV radiation on protoplanetary disks have been observed in Orion, but the general impact of even more intense radiation fields characterizing massive clusters are not yet well understood.

We propose a deep (100 ks) Chandra ACIS-I observation of the young ($\sim 3\,Mrs$) open cluster Pismis 11, hosting the Blue Hyper-Giant (BHG) star HD 80077, one of the most luminous stars in our Galaxy. Its ionizing flux is one order of magnitude more intense than those of early O stars and blue supergiant (BSG) stars, and, unlike the Luminous Blue Variables (LBV), it is not absorbed by dense circumstellar material. HD 80077 has completely dominated the radiation field in Pismis 11 and the cluster therefore presents an unusually well-controlled laboratory to study the effects of intense UV-FUV irradiation on star and planet formation. The proposed observation will detect cluster members down to $1\,M_{odot}$. Combined with existing Spitzer photometry and new deep optical photometry the study will provide an accurate assessment of the cluster age, IMF and protoplanetary disk fraction.

Scientific Rationale: In recent years several studies have aimed to understand whether the star formation process and the evolution of protoplanetary disks (*proplyds*) are similar in the various star forming regions in our Galaxy, or whether different environments strongly affect the final product of star and planet formation.

Since the direct images of proplyds in the Orion Nebula Cluster (ONC) by the Hubble Space Telescope [1], we know that UV radiation from OB stars induces the photoevaporation of nearby circumstellar disks [2], which can be dissipated in less than $1\,Myr$. Since planetary formation occurs in circumstellar disks on timescales of some Myrs (e.g. [3]), the important implication of this result is that close to ionizing sources, such as OB stars, planets have less time, and lower chances to form.

In order to understand in what astrophysical environments planets can form, and considering that our Sun likely formed in a stellar cluster that hosted some OB stars [4], it is important to fully understand the effects of massive stars on the evolution of nearby circumstellar disks. Recent studies of massive young clusters such as NGC 2244 [5] and NGC 6611 [6] have shown that in the early stage of cluster evolution ($1-3\,Myrs$) OB stars can dissipate only very nearby disks (closer than $0.5-1\,pc$). Disks in the outer cluster evolve unperturbed, even in clusters hosting tens of OB stars such as NGC 6611. To date, the only evidence of effects on circumstellar disks induced at large distances from O stars is the presence of evaporating proplyds in Cyg OB2 (which hosts hundreds of OB stars) at a distance of $5-15\,pc$ from the cluster center [7].

The UV radiation emitted from OB stars is also expected to photoevaporate the collapsing envelops of embedded protostars (Class 0/I) that have emerged from the parental cloud and are then exposed to the ionizing radiation. This process should halt the mass accretion onto protostellar cores that experience a high ionizing flux. The discovery of the evaporating gaseous globules in M16 [8] has prompted suggestions that such a process is ongoing, but the Initial Mass Function (IMF), which is the stellar mass distribution at birth [9], seems to be universal in our Galaxy and independent of the star forming environment. In fact, the IMF of several massive clusters do not show significant deviations from the universal law [i.e. 10,11]. This implies that the timescales necessary for the ionizing radiation provided by OB stars to dissipate the protostellar envelops are too long compared with the accretion timescale in the Class 0/I phase ($0.1\,Myrs$), and then that the massive content of clusters do not influence their IMF.

There is no strong evidence, then, suggesting that OB stars affect both planet formation and the IMF in their entire parental cluster. However, the intensity of the ionizing flux and stellar wind from OB stars changes drastically during their evolution. Ionizing radiation and stellar winds in giant OB stars are hundreds of times more intense than in Main Sequence (MS) OB stars. Besides, among the evolved OB stars, BHG stars emit more ionizing flux than BSG and LBV stars. We have calculated the ionizing flux from OB stars in the Far UltraViolet (FUV) using the results in [12, 13, 14]. We focused on the FUV flux because the Extreme UltraViolet (EUV) radiation is more easily absorbed by the intracluster medium (the EUV flux is completely absorbed within an extinction $A_V \sim 1^m$). Given its spectral type, the BHG star which is the subject of this proposal (HD 80077, a B2I star) emits 45.3% of its total radiation in the FUV regime, which means $L_{FUV} = 9.03 \times 10^5\, L_{\odot}$. The same calculation for $\Theta^1\, Orionis$ (spectral type O6), which is the most important ionizing source in the Trapezium, gives a FUV luminosity equal to $7.9{\times}10^4\, L_{\odot}$, implying that the ionizing effects induced by HD 80077 are much more intense than those in known nearby clusters containing MS O stars.

A similar comparison holds between BSGs and most of the LBV stars. The most luminous among the LBV stars do emit ionizing fluxes comparable to that of BHG stars. The most impressive LBV star is $\eta\, Carinae$, for which we found $L_{FUV} = 6.2 \times 10^5\, L_{\odot}$. However, the ionizing radiation of the most extreme LBV stars is highly absorbed by the dense circumstellar material ejected during their eruptive phases. For instance, the Homunculus nebula surrounding $\eta\, Carinae$ absorbs 80% of the optical and UV radiation from the central star [15]. BHG stars, then, affect the evolution of nearby young stars much more efficiently than any other type of evolved massive star.

Very few BHG stars are known in the Milky Way [16]. The closest to the Sun are HD 80077, associated with Pismis 11 ([17,18]), ζ^1 Scorpii, which is part of the Scorpius OB association, and Cyg OB2 #12, associated with the Cyg OB2 cluster. They are the most luminous stars in our Galaxy, with $log\,(L_{bol}) = 6.3\, L_{\odot}, 5.93\, L_{\odot}, 6.28\, L_{\odot}$ respectively [19,20]. Among them, HD 80077 is the best target to study the effects of UV-FUV radiation on the evolution of nearby low mass stars. In fact, ζ^1 Scorpii is $31'.5$ away from NGC 6231, corresponding to a projected distance of about $7\, pc$, while HD 80077 is less than $2\, pc$ away from the center of Pismis 11; and in Cyg OB2 it is impossible to distinguish the effects due to the radiation from Cyg OB2 #12 from those due to the hundreds massive stars hosted in the cluster, while Pismis 11 hosts only two late O stars. Other BHG stars have been identified in particularly massive environments such as Westerlund 1, the Galactic center, and the Large Magellanic Clouds. But these regions are too distant to resolve the surrounding low mass population with Chandra or with the other existing X-ray observatories.

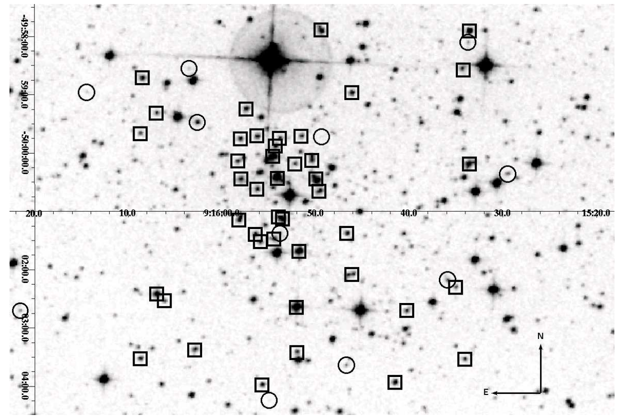

Figure 1: DSS-I image of HD 80077 (the most luminous star in the field) with a size of $10' \times 7'$. Circles mark stars with excesses in 2MASS K band; squares mark the candidate cluster members [18].

Fig. 1 shows a DSS-I image of Pismis 11 and HD 80077, with known members marked. The membership of HD 80077 to Pismis 11 is secure from several lines of evidence. Spectroscopic studies have confirmed its high luminosity and intense mass loss rate consistent with the distance to Pismis 11 [18,20]; its proper motion is compatible with that of other OB members of Pismis 11 and it is not a runaway star [18]; and the reddening in the cluster increases toward HD 80077 [17]. New evidence will be provided by unpublished spectral observations (Marco A., private communication).

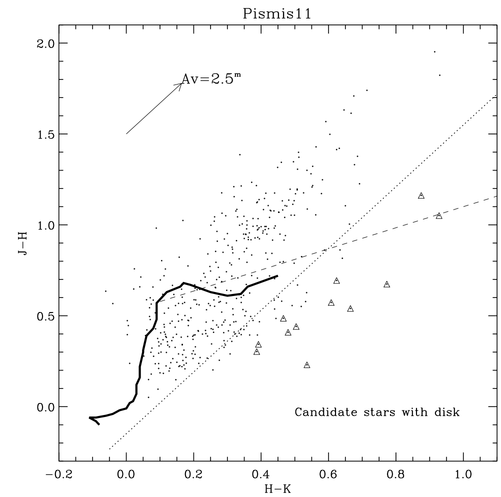

Figure 2: $J-H$ vs. $H-K$ diagram for the stars (points) of Pismis 11. Triangles mark candidate stars with infrared excesses. The thick solid line is the ZAMS [23]; the dotted line separates the locus of stars with intrinsically red $H-K$ colors from those of normal stars; the dashed line is the T-Tauri locus [24]. The arrow marks the reddening vector.

Objectives: Pismis 11 is a young cluster, with the age constrained to 3-5 Myrs [18,20]. Considering a ZAMS mass of HD 80077 of 85 $M_\odot$ [21], we expect that this exceptional star affected the cluster evolution in the last $1.5 - 2\,Myrs$ (we calculated in its MS phase a $L_{FUV} > 2.5 \times 10^5\,erg/s$). Assuming that the cluster is characterized by the universal IMF, and given the presence of 54 identified members earlier than A0 [18], among which there are two O stars and the BHG, the cluster must host a significant population of low mass stars. Besides, following the decline of disk frequency with cluster age in young clusters [22], a significant fraction of disk-bearing members (between $\sim$ 50% and $\sim$ 20%) is expected. However, there are just a few candidate stars with disks down to $1\,M_\odot$ (the mass limit of the 2MASS data at the distance of the cluster) from the 2MASS $J-H$ vs. $H-K$ diagram of sources in Pismis 11 area (Fig. 2). We note that 2MASS disk selection is notoriously incomplete, but at face value this finding is compatible with the following two scenarios.

The cluster's IMF deviates from the universal law: a possible explanation could be that the cluster lacks the expected low mass population. Since the cluster is too young for the low-mass stars to be dispersed, this paucity of low mass stars would be related to a fast dissipation of the collapsing molecular cloud by HD 80077, prematurely halting their formation. This process would be less influential for intermediate to high mass stars, since the timescale for their protostellar phase is shorter than for low mass stars.

Disks in the cluster have been dispersed: the low-mass population of the cluster follows the universal IMF, but a very small fraction of them still host a disk. In this case the UV radiation from HD 80077 has dissipated the circumstellar disks not only in its vicinity, as expected, but in the entire cluster (since the cluster center is $2\,pc$ away from the BHG star). The presence of a BHG star creates, then, a hostile environment for the formation of planetary systems.

Either of these two scenarios would be of profound importance, even if in order to test or refine them we need an accurate census of the low-mass population and the disk fraction. The proposed *Chandra* ACIS-I observation, in combination with existing and upcoming optical and infrared data, will allow us to identify Pismis 11 members down to $1\,M_\odot$, including those that have already dissipated their disks and are very hard to select without the use of X-ray data. Spitzer/IRAC data are much more sensitive to disk emission than 2MASS, whose K band only probes hot dust in the very inner disk. The existing Spitzer data are sufficiently sensitive to reach down below $1\,M_\odot$ (the observations have the same depth of the GLIMPSE survey, reaching subsolar masses for clusters at the distance of Pismis 11), and allow us to assess the true disk fraction. The combined data will then enable us to assess the true extent to which disks or low mass stars are influenced by extreme irradiation from HD 80077. Stellar masses will be inferred from the photometry, in order to identify the IMF turn-over and slope and compare them with those of other clusters, while disks fraction will be evaluated by identifying disk-less and disk-bearing members.

X-ray emission from HD 80077: the requested observation will also give us the chance to study the X-ray properties of HD 80077. Despite being particularly bright in the optical and infrared, LBV stars are usually weak X-ray sources, the only exception being known binary systems where colliding winds from the two component can result in intense and hard X-ray emission [25]. The same evidence holds for known BHG stars. The most peculiar exception to this is the BHG star Cyg OB2 #12, which shares several similarities with HD 80077. Cyg OB2 #12 is extremely bright, with $log\,(L_X) = 33.39\,erg/s$ [26], and an X-ray spectrum dominated by two components with $kT_1 = 0.73 \pm 0.16\,keV$ and $kT_2 = 1.8 \pm 0.4\,keV$ [27]. Since there is no evidence for binarity [19], the high luminosity and the hot component are better explained with the Magnetic Colliding Wind Scenario, where hot X-ray emission is created by plasma confined in the intense dipolar magnetic field and colliding in the magnetic equatorial plane. Given the similarity with Cyg OB2 #12, this characteristic might be shared also by HD 80077, which also lacks evidence for binarity. HD 80077 is then a very interesting target to be studied in X-rays.

Feasibility: To reach our goals, we request a total of 100 ks of observation time. This exposure has been estimated in order to detect cluster members down to $1\,M_\odot$, which is the limit of the existing and upcoming photometric data. In fact, together with published $UBVRI$ data down to $V \sim 18^m$ (down to 2.5 $M_\odot$ at the cluster distance of 3.6 kpc, [18]), observations in $u'g'r'i'H\alpha$ bands for the VPHAS survey, in which some of the CoI of this proposal are involved, will be available by the end of this year. The limit of the VPHAS observation is $r' = 21^m$, roughly corresponding to $1\,M_\odot$ at the distance of the cluster, which is the same limit of existing 2MASS data. The cluster has also been observed with Spitzer/IRAC (AORs 23700736 and 23707392, PI Majewski) providing an efficient tool for the selection of low-mass disk-bearing members.

To estimate the lowest X-ray emission expected from a young star at $1, M_\odot$, we used the data from the Chandra Ultradeep Orion Project (COUP, [28]), which is the only X-ray survey of a young cluster ($\sim 1\,Myr$) complete down to $0.1\,M_\odot$. In the COUP data, the lowest L_X observed from $1\,M_\odot$ members is $log\,(L_X) = 29.8\,erg/s$, corresponding to a flux $F_X = 4.1 \times 10^{-16}\,erg/cm^2/s$ at the distance of Pismis 11. Using WebPIMMS v4.5 and adopting a Raymond-Smith thermal emission spectrum with $kT = 1.37\,keV$ and $N_H = 9.4 \times 10^{21}\,cm^{-2}$, we estimate that we will observe about 5 photons in 100 ks from the faintest cluster members with $1\,M_\odot$. By our experience, performing source detection with PWDetect [29] and CIAO Wavdetect [29] and given the low background expected, 5 net counts are enough for the detection. Photons extraction and spectral analysis will be performed with *Acis Extract* software [30].

1 References

[1] O'dell, C. R. et al., 1993, ApJ, 410, 696. [2] Hollenbach, D., 1994, NASA STI/Recon Technical Report N, 1, 47002. [3] Bromley, B. et al., 2011, ApJ, 731, 101. [4] Adams, F. C., 2010, ARA&A, 48, 47. [5] Balog, Z. et al., 2007, ApJ, 660, 1532. [6] Guarcello, M. G. et al., 2010, A&A, 521, 61. [7] Wright N. J., 2012, ApJ, 746, 21. [8] Hester, J. J. et al., AJ, 111, 2349. [9] Bastian N. et al. 2010, ARA&A, 48, 339. [10] Oliveira, J. M. et al., 2009, MNRAS, 392, 1034. [11] Wright, N. J. et al., 2010, ApJ, 713, 871. [12] Parravano, A. et al., 2003, ApJ, 584, 797. [13] Kenyon, S. J. et al., 1995, ApJs, 101, 117. [14] Martins, F. et al., 2005, A&A, 436, 1049. [15] Pagel, B. E. J., 1969, Nature, 221, 325. [16] van Genderen, A. M., 2001, A&A, 366, 508. [17] Moffat, A. F. J., & Fitzgerald, M. P., 1977, A&A, 54, 263 . [18] Marco, A. et al., 2009, A&A, 493, 79. [19] Clark J. S. et al., 2012, Arxiv, 202.3991C. [20] Carpay, J., de Jager, J., Nieuwenhuijzen, H., Moffat, A., 1989, A&A,216, 143. [21] Knoechel, G. et al. 1982, A&A, 110, 263. [22] Haisch Jr, K. E. et al. 2001, ApJ, 553, L 153. [23] Siess, L., Dufour, E., & Forestini, M., 2000, A&A, 358, 593. [24] Meyer, M. R., Calvet, N., Hillenbrand, L. A., 1997, AJ, 114, 288. [25] Nazé et al., 2012, A&A, 538, 47. [26] Wright, N. J. et al., 2009, ApJ, 184, 84. [27] Albacete-Colombo et al., 2007, A&A, 464, 211. [28] Getman K. et al., 2005, ApJS, 160, 319. [29] Damiani, F. et al., 1997, ApJ, 483, 370. [29] Freeman, P. E. et al., 2002, ApJS, 138, 185. [30] Broos P. S. et al 2010, ApJ, 714, 1582.