CONFERENCE SUMMARY: STELLAR FEEDBACK IN THE ISM: CELEBRATING THE LIFE AND WORK OF YOU-HUA CHU(朱有花)

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RESUMEN

En este resumen de la conferencia, primero ofrezco algunas notas históricas sobre mi propia colaboración con You-Hua Chu y sobre el descubrimiento de rayos X de superburbujas por Margarita Rosado S. Luego considero el tema central de la conferencia, la retroalimentación estelar, y cómo las interacciones entre los vientos estelares y el medio interestelar pueden limitar o mejorar los efectos de la retroalimentación en comparación con modelos que incluyen solo explosiones de supernovas. Finalmente, reviso los resultados en otras áreas cubiertas por la conferencia, incluidos los planetas y su formación, los remanentes de novas y supernovas, diferentes temas en la evolución estelar y la interacción con el medio interestelar, los cúmulos estelares, los estudios observacionales y las técnicas numéricas y de observación.

ABSTRACT

In this conference summary I first provide some historical notes on my own collaboration with You-Hua Chu and on the discovery of X-rays from superbubbles by Margarita Rosado S. I then considere the central subject of the conference, stellar feedback, and how interactions between stellar winds and the interstellar medium can limit or enhance the effects of feedback compared to models including only supernova explosions. Finally, I review results in other areas covered by the conference, including planet and formation, nova and supernova remnants, different topics in stellar evolution and interaction with the interstellar medium, star clusters, observational surveys, and observational and numerical techniques.

Key Words: HII regions — ISM: jets and outflows — stars: mass-loss — stars: pre-main-sequence

1. HISTORICAL

1.1. Personal

I first met You-Hua Chu while I was a graduate student visiting Michael Norman at the National Center for Supercomputing Applications (NCSA) at the University of Illinois in 1987. I listened in to You-Hua and Mike in his office as they considered the consequences of a blast wave running through a clumpy interstellar medium (Norman et al. 1988). I explained to her that I was working on a thesis on the theory of superbubbles. Shortly afterwards, she emailed a series of cogent questions about X-ray emission from superbubbles, which my thesis advisor Dick McCray strongly suggested I engage with. That was excellent advice that led to our description of X-ray emission from superbubbles in the Large Milky (Oey and others' suggested decolonial renaming from Magellanic) Cloud (LMC; Chu & Mac Low 1990) using the *Einstein* data taken by Rosado and described in the next section. Our collaboration was a major factor in my early career, leading to seven papers together.

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We also collaborated in advising students, all of whom have contributed to this conference. The first was Guillermo Garcia-Segura, who after an initial observational paper, turned out to be a theorist whose work on the structure of bubbles in timevarying stellar winds has stood the test of time. The second was Sean Points, who was most certainly not a theorist, but has had a distinguished career supporting CTIO and surveying the Magellanic Clouds. Finally came Chao-Chin Yang, who led our demonstration that Toomre gravitational instability of stars and gas can explain the locations of star formation in the LMC (Yang et al. 2007). He then joined my group and moved from working on galactic disks to working on protostellar disks and planet formation, where he continues to have a substantial impact.

1.2. X-ray Observations of Superbubbles

Margarita Rosado Solís contributed a history of how the first X-ray observations of superbubbles came to be, which I include here.

Most of you do not know but I have the honor of having contributed with my small grain of sand to the discovery of Xray emission from superbubbles. I was a PhD student when my observing proposal with the Einstein Satellite of deep exposures of several superbubbles in the LMC including the superbubbles N70 and N185 was accepted. Indeed, at that time I have just measured the high expansion velocities of N7 and N185 by means of Fabry-Perot interferometry (about 70 km/s) and I have computed the X-ray luminosities submitting a proposal to the Einstein Observatory together with my adviser Guy Monnet. The Rosado & Monnet proposal was accepted by Einstein Observatory board and the observations carried out giving the result of the detection, for the first time, of X-ray emission from the superbubbles N70 and N185, among other superbubbles.

We submitted an article reporting those successful results that was rejected by an anonymous referee that argued that it was only noise (at that time the Einstein Observatory instrumental function was concealed for alien users as me, so that it was really hard to answer to the aggressive referee). Years after, our observations were used by You-Hua Chu and Mordecai Mac Low showing that indeed there was X-ray emission from those superbubbles. In fact, bubbles and superbubbles were unexpected objects that successfully emit in X-rays besides the binary compact X-ray sources. Thanks to that observing proposal the Xray emission from superbubbles started to be studied from the X-ray observatories.

2. STELLAR FEEDBACK

Stellar feedback is required to understand galaxy evolution, as Pittard summarized in his talk (i.e. Dalla Vecchia & Schaye 2008). Without including effective stellar feedback, galaxy models form objects far smaller and denser than observed. In this section I summarize how our understanding of this process was advanced during the conference.

The initial focus of stellar feedback modeling was momentum and energy transfer from supernovae (SNe). The momentum injection from SNe in a uniform medium is well understood (e.g. Pittard 2019). However, the consequences of an inhomogeneous medium remain controversial, with Martizzi et al. (2015) and Zhang & Chevalier (2019) finding a 30% reduction in momentum injection, while Kim & Ostriker (2015) and Walch et al. (2015) find no reduction. Numerical algorithms for adding SN feedback have tended to fail at the numerical resolutions practical for whole galaxy or cosmological models. Only recently have examples been described of apparently resolution-independent algorithms such as FIRE-2 (Hopkins et al. 2018).

However, the story is likely to be more complicated than that for several reasons. First, Pittard noted that it is likely that not all massive stars explode as SNe. Smartt (2015) found that no star with an initial mass exceeding 20 M_{\odot} has been observed to explode. Models by Sukhoold et al. (2016) indeed suggest that direct collapse dominates the outcomes for stars greater than that mass, and even isolated masses down to as low as 15 M_{\odot}. Oey noted that several groups have found that low-metallicity stars have a lower threshold for direct collapse (Heger et al. 2003; Zhang et al. 2008; O'Connor & Ott 2011; Sukhold et al. 2016). Second, Oey also noted that there can be a several megayear delay before SNe begin. At high densities, neglecting other forms of stellar feedback such as stellar winds can lead to dramatically higher star formation efficiency (SFE). However, stellar winds can be an order of magnitude weaker for substantially subsolar luminosities (Jecmen & Oey 2023).

A further puzzle is that observed stellar wind bubbles often appear to expand too slowly and have too little X-ray emission compared to what would be expected from the Weaver et al. (1977) dynamical model. Chu gave an example from Nazé et al. (2001), showing a 15 pc bubble expanding at only 15-20 km s⁻¹. Oey reviewed the idea that catastrophic cooling of the hot shocked wind region in the interior can shift the solution from the energy conserving solution (Pikel'Ner 1968; Avedisova 1972; Castor et al. 1975; Dyson 1975; Weaver et al. 1977) to the momentum-conserving solution (Steigman et al. 1975). This likely happens in superbubbles as well. The example of N79 in the LMC was described by Rodriguez, presenting results in preparation by Webb & Rodriguez. They find that the diffuse Xray emission from this super star cluster is an order of magnitude below that predicted by Weaver et al. (1977) or Chu & Mac Low (1990). Further examples of this phenomenon given by Oey include Saken et al. (1992); Brown et al. (1995); Oey (1996); Oey & Kennicutt (1998); Cooper et al. (2004); Smith et al. (2005) and Oey et al. (2009). Pittard summarized models of efficiently cooling bubbles, primarily due to turbulent mixing at the interface between hot and cold gas (Rogers & Pittard 2013; Geen et al. 2015; Haid et al. 2018; Lancaster et al. 2021). An analytical model of a leaky bubble is an alternative (Harper-Clark & Murray 2009), although that presupposes a lower-density region to leak into, which isn't necessarily available.

Oev argued that at low metallicity, super star clusters fail to effectively drive winds at early times because of the reduced stellar wind strengths expected. This leads to high-density gas being retained near the clusters (Jecmen & Oey 2023), catastrophic cooling (Silich et al. 2004; Wünsch et al. 2007), and thus insufficient time to launch a superwind (Danehkar et al. 2021). Feedback during this period is then radiation dominated (Freyer et al. 2003; Krumholz et al. 2009; Komarova et al. 2021), leading to higher SFE (Krause et al. 2012; Silich & Tenorio-Tagle 2018), greater gas clumpiness allowing Lyman continuum to escape (Jaskot et al. 2019). and smaller superbubbles. The discovery by a group including You-Hua of diffuse nebular CIV emission around the slowly expanding superbubble Mrk 71 supports this scenario (Oey et al. 2023). Even at solar metallicity, models by Polak et al. (2023) find that centrally-concentrated gas clouds with masses approaching $10^6 M_{\odot}$ have high SFE and do not effectively drive superwinds for several megayears.

The same physics that is important in determining stellar wind bubble dynamics may also act in planetary nebulae, as reviewed by Guerrero. In a series of papers Toalá & Arthur (2014, 2016, 2018) showed that thin-shell and Rayleigh-Taylor instabilities, along with shadowing of ionizing radiation, would mix the contact discontinuity between hot and cold gas in these systems as well, reducing Xray emission compared to pure thermal conduction. This has been associated with an observed increase in intermediate ions such as N V at the discontinuity (Fang et al. 2016), and, as Richer pointed out, in broadening of UV lines reaching 5–20 km s⁻¹.

Wang noted that observational constraint of these mixing models can be achieved using thermal plasma models of X-ray spectra that include charge exchange (Zhang et al. 2014). Because charge exchange is proportional to the ion flux into the contact discontinuity, it can constrain the product of the flow speed and the effective interface area produced by mixing.

3. COFFEE BREAK

Coffee breaks at the IA-UNAM in Ensenada had a spectacular view, as shown in Figure 1.

4. SHINY RESULTS

In this section I pick out results reported at the conference that I judged to be of particular interest, but do not follow a single theme.

4.1. Planet Formation

Recent observations with the Atacama Large Millimeter/submillimeter Array (ALMA) have dramatically sharpened our view of the early stages of disk formation. This period increasingly looks likely to be the crucial period for planet formation. Two major surveys have shown stark differences in the appearance that disks show over the first few megayears of their lives. The eDISK survey (Ohashi et al. 2023) focused on class 0 disks shows rather uniform disks, while the DSHARP survey (Andrews et al. 2018) focused on class I and II disks famously shows a wide variety of rings, spirals, gaps, and other structures. The jury is still out on whether the lack of structure at early times is an optical depth effect—earlier, more massive disks might be too optically thick to show midplane structure—or whether the development of disk structure correlates with the growth of gas giant planets. This is, of course, complicated by the argument on whether disk structures are actually caused by planet formation or other mechanisms, as only two planets, PDS 70b and PDS 70c, have actually been observed in a disk with a gap (e.g. Benisty et al. 2021).

An alternative proposal for producing structure in observed dust disks is the impact of non-uniform accretion onto disks. Segura-Cox reviewed observational evidence for streamers of gas accreting onto protoplanetary disks (ALMA Partnership et al. 2015; Segura-Cox et al. 2020; Garufi et al. 2022; Flores et al. 2023). Kuznetsova et al. (2022) has made the argument that the impact of streamers on disks forms pressure bumps that can trap gas, providing both a promising site for rapid planet formation and an alternative explanation for the formation of the observed ring structures.

Once disks form, dust settles to the midplance, where it begins to coagulate into grains that can grow large enough to start decoupling from the gas. When stopping times grow towards orbital time scales (Stokes number approaches unity), streaming instability sets in, gathering particles into dense clumps that can become self-gravitating. Yang reviewed high-resolution models (Yang & Johansen 2014; Schäfer et al. 2017) of the streaming instability that show a remarkable resemblence to the size distribution of the cold, classical Kuiper Belt observed by Kavelaars et al. (2021). This region of the Kuiper



Fig. 1. View from coffee break at IA-UNAM Ensenada.

Belt is sufficiently low density that the objects are expected to retain their primordial size distribution, making it an excellent laboratory for study of planetesimal formation.

4.2. Star Formation

Two models for star cluster formation were discussed. Grebel reviewed simulations showing that collisions of discrete spherical clouds with different masses in the interstellar medium produce characteristic U-shaped clouds with cavities morphologically similar to observed H II regions such as RCW 120, S44, or S36. However, Arthur's talk showed that the champagne flow morphology characteristic of massive star formation in a region with a density gradient equally well describes these regions. Vázquez-Semadeni argued that global hierarchical collapse in a turbulent interstellar medium better describes the star formation process. Turbulent flows produce a continuous density distribution poorly described by isolated, discrete clouds, but easily leading to the density gradients needed to produced U-shaped bubbles.

Another issue discussed was the structure of the magnetic fields that can prevent or allow gravitational collapse and star formation. On the scale of a filament dozens of parsecs long, Stephens showed a magnetic polarization map revealing that although the field lies predominantly perpendicular to the filament, there are also multiple regions where it is parallel. This suggests that although the field is important to shaping the flow, it does not always dominate. Looney used ALMA 870 μ m polarization to demonstrate grain alignment in the disk of HL Tau (Stephens et al. 2023), presumably by the local field in the disk. Sharma compared polarization measurements towards the outflow and envelope around HD 200775 taken with Planck and AIMPOL in India, showing how the low-resolution, large-scale Planck results average over the small-scale structure in the region.

4.3. Nova and Supernova Remnants

Orozco-Duarte reviewed the varied morphology of SN remnants, and compared them to simulations of three typical scenarios: an explosion within a bow shock produced by a star moving supersonically with respect to the surrounding medium, a explosion within a star's (spherically symmetric) birth cloud, and an explosion near the edge of a filament an order of magnitude denser than the surrounding medium, which allow reproduction of many observed SN morphologies. Orozco-Duarte et al. (2023) showed that a superbubble in the filament scenario will have offcenter SN explosions that cleanly explain the observed soft X-ray luminosity, supporting the hypothesis originally proposed by Chu & Mac Low (1990).

Santamaria and collaborators had a poster showing a morphological catalog of nova remnants. The frequent occurrence of fragmented shells is striking. Toraskar et al. (2013) used simulations to demonstrate that this is exactly the morphology expected from repeating nova explosions separated by periods of hibernation.

A three-dimensional model of the Gemini-Monoceros X-ray enhancement using eROSITA data (Knies et al. 2024) was reviewed by Sasaki. Rather than the usual conclusion that there are two overlapping remnants in the region, they found a total of four objects overlapping in various ways.

The magnetic field in the region behind a SN blast wave was also reviewed by Sasaki. Evolving small scale structure oriented perpendicularly to the blast wave was identified by Matsuda et al. (2020).

Type Ia remnants were considered by several speakers. Pan showed the effects of Type Ia ejecta hitting companion stars (Pan et al. 2012), while Chuan-Jui Li showed the effect of circumstellar medium around Type Ia SNe on their remnants. Li et al. (2021) showed evidence that the presence of circumstellar medium could be more common than expected, and derived an evolutionary sequence for these remnants.

4.4. Stars in all their variety

4.4.1. Moving Stars

Arthur and Mackey both emphasized that stars with strong stellar winds moving through the ISM produce distinctive bow shocks (van Buren & Mac Low 1992) and bow waves (Henney & Arthur 2019a,b,c). These can include wind bow shocks such as NGC 7635 (Green et al. 2019) or ζ Oph (Toalá & Arthur 2016; Green et al. 2019), bow waves such as the boundary of the heliosphere, dust waves, and radiation bow shocks. Wind bow shocks around stars with fast enough winds can even be detected in the X-ray (Toalá & Arthur 2016; Green et al. 2022). Orozco-Duarte showed the consequences of an SN explosion within a bow shock (Orozco-Duarte et al. 2023).

4.4.2. Very Massive Stars

The hunt for very massive stars with masses well above 100 M_{\odot} has extended for decades. The bright spot R136 at the center of You-Hua's favorite H II region, 30 Doradus, was already hypothesized to be a single 1000 M_{\odot} object in the early 1980s. One of her early scientific successes was splitting that spot into multiple components, demonstrating that it is a cluster and not a single star (Chu et al. 1984). However, Smith reviewed the evidence for very massive stars with masses far in excess of 100 M_{\odot} dominating the core of that cluster, most importantly the strong He II emission lines observed there (Crowther et al. 2016). Other super star clusters also show similar emission, arguing that very massive stars are quite generally present in these exceptional objects, even out to high redshift. Wofford also reviewed this evidence in other objects, such as NGC 3125-A1 (Martins & Palacios 2022).

4.4.3. Close Binary Evolution

There was, of course, extensive discussion of the evolution of close binaries, which can lead to anything from a planetary nebula to a kilonova produced by a neutron star merger. Ricker showed the results of the evolution of a tight binary where mass transfer from the more massive primary to the secondary prior to the SN explosion of the primary results in the secondary evolving faster than it would otherwise, allowing a common envelope to form in the envelope of the secondary encompassing the neutron star remnant of the primary. The end result is a neutron star binary that can merge in a kilonova. Estrada showed that mass transfer from a low mass star onto a compact companion can strip enough mass away to leave a planetary-mass object, which he dubbed a "Chupiter".

Garcia-Segura showed his increasingly detailed models of common envelope evolution that now couple one-dimensional MESA models of post-main sequence stellar evolution to three-dimensional Flash models (begun by Ricker & Taam 2012) and aspherical two-dimensional ZEUS models (Garcia-Segura et al. 2018, 2020, 2021, 2022). The broad variety of planetary nebula morphologies can be captured by this technique to a surprising extent.

Richer studied the velocity gradients and line broadening in planetary nebula shells, showing that the ordered velocity gradient can not explain the full line widths observed. This suggests that turbulent energy in the shell could be as much as 25% of the thermal energy of the plasma, something not accounted for in previous studies. Weis used similar line observations of AG Carinae to demonstrate that it is not elliptical, but instead bipolar, a morphology that is obscured by its pole-on orientation towards the Earth.

Haberl showed observational evidence that the population of high-mass X-ray binaries correlates well with the star formation rate 25–60 Myr prior in the Small Milky Cloud (Antoniou et al. 2010), but in the LMC correlates with the rate 6–25 Myr prior, and with a formation efficiency 17 times lower in the higher metallicity region (Antoniou & Zezas 2016).

4.5. Star Clusters

Stars clearly form in a non-uniform manner. This was classically thought of as occurring in two modes of star formation: clustered and isolated. Grebel emphasized in her review, however, the result of Bressert et al. (2010) that young stellar objects show a continuous Gaussian distribution of surface densities with a peak in the region within 500 pc of the Sun of 22 pc⁻² and a dispersion in the log of the surface density of 0.85. Regions at the high end of this distribution get identified as clusters, but the choice of a cutoff between clustered and isolated star formation is arbitrary.

Similarly, the mass-radius relation of observed clusters appears to show a continuous distribution from open clusters through globular clusters, if one takes into account that young massive clusters can have masses and radii intermediate between open clusters and old globular clusters (Portegies Zwart et al. 2010). The evolution of clusters in the massradius plane can be seen in action as recent observations (e.g. Drew et al. 2019; Meingast et al. 2021) show that open clusters are often accompanied by enormous halos of unbound stars of the same age occupying a region as much as an order of magnitude larger than the tidal radius of the central cluster.

4.6. Surveys

Multiple observational surveys were reviewed. Rodriguez described the addition of *James Webb Space Telescope* data on 19 spiral galaxies to the PHANGS survey of nearby galaxies at high resolution. Eight infrared bands were imaged with the MIRI and NIRCAM instruments, providing access to stellar photospheric emission with low obscuration, polycyclic aromatic hydrocarbons, dust continuum, and silicate absorption. Dale showed how the combination of the LEGUS (Calzetti et al. 2015), PHANGS (Lee et al. 2022; Leroy et al. 2021; Emsellem et al. 2022) and GOALS (Armus et al. 2009) surveys shows a relationship between stellar mass and star formation rate spanning five orders of magnitude.

Maschmann used the PHANGS-HST data to study the ages of clusters across the mass-star formation rate plane. Galaxies with high star formation rates compared to the typical value (the so-called main sequence) have plenty of middle-aged clusters, while galaxies with low rates tend to be missing them. (The figure showing this effect was a contender for the most data presented in one figure, as color-color diagrams for every galaxy were presented in a single mass-star formation rate plot.)

Points described the Milky Clouds Emission Line Survey in its most recent version using the Dark Energy Camera. Williams used the Survey to identify a large number of SN remnants across the LMC. Sánchez reviewed the Local Volume Mapper, which uses integral field units the size of the full moon to take spectra at 30" resolution sampling the full sky and densely covering the plane of the Milky Way disk, as well as Orion and the Milky Clouds.

Haberl reviewed the eROSITA all-sky X-ray surveys, the first four of which have been completed, and the fifth of which was truncated by unfortunate geopolitical events, but not before covering the northern half of the LMC. Altogether, some LMC sources have as much as three weeks of observation time. Grishunin reviewd the APEX Legacy LMC CO-line Survey, which gives 5 pc resolution across 85% of the LMC, resolving clouds with masses as low as 300 M_{\odot} .

4.7. Numerical Techniques

Several talks emphasized the need to pay close attention to numerical issues to ensure that the physics is being captured. Resolution of physical length scales is a near universal issue. Pittard showed a quantitative criterion for how well the source region for a stellar wind bubble must be resolved to ensure that a bubble forms at all, and further with the correct radial momentum. Mackey showed that increasing the resolution of a bow shock by a factor of four dramatically increases the amount of mass entrained from the contact discontinuity between shocked wind and swept-up ISM by Kelvin-Helmholtz instabilities in the tail of the structure. Mathew checked the ionization structure of an adiabatic shock across a factor of 10 in linear resolution, finding that 1024 grid points does a very good job.

4.8. Observational Techniques

The past and the future of the observation of bubbles and SN remnants was discussed. Toalá reminded us of the dramatic advance in imaging capability represented by the transition from the *Einstein Observatory* to *XMM-Newton* using the example of images of the stellar wind bubble S308. He brought us up to the present day with an infrared spectrum of extraordinary resolution of WR124, taken with the *James Webb Space Telescope* MIRI integral field unit. Then, he compared the *XMM* spectrum of S308 to simulated spectra expected from *XRISM*, *AXIS*, and finally, and most extraordinarily, the exquisite spectrum out to 3 keV expected from the *Athena* WFI.

Long emphasized that XRISM will be able to take high-resolution spectra of Galactic SN remnants, while Athena will extend that capability to nearby galaxies. These spectra will allow measurement of rarer elements than possible to date, constraining explosion mechanisms. *IXPE* will measure the polarization of Galactic SN remnants, constraining their field structures and thus their particle acceleration properties. Meerkat and upcoming radio telescopes can now image remnants at radio wavelengths with the angular resolution we are accustomed to from optical observatories. This will allow discovery and characterization of remnants in other galaxies.

5. RECOGNITION

The scientific organizing committee of this conference felt that the best recognition we could make of You-Hua Chu's scientific career was to include her in Wikipedia. The stringent standards currently applied for notability of entries allowed into this encyclopedia indeed show the importance of her career. See en.wikipedia.org/wiki/You-Hua_Chu for the current version of this page. A page has since also been added in simplified Chinese (zh.wikipedia. org/wiki/%E6%9C%B1%E6%9C%89%E8%8A%B1).

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