Advective-acoustic cycle in a shallow water standing accretion shock experiment

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The surface height in a shallow water accretion flow experiment is measured by means of Fourier transform profilometry and the fluctuations are characterized. The shallow water analog of the standing accretion shock instability (SWASI) appears with an azimuthal mode number of one in the presence of supercritical flow in the radial direction. During the occurrence of the SWASI, surface gravity waves preferentially propagate radially outward. This is consistent with the advective-acoustic cycle driving the shallow water analog of the standing accretion shock instability.

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I. INTRODUCTION

Once a star with a mass of approximately 12–25 solar masses reaches the end of its life cycle, the iron core at the center starts to collapse [1]. When reaching nuclear densities, the collapse comes to an abrupt halt. The associated rapid deceleration generates a shock wave which propagates outward through the still accreting matter of the outer stellar shells, leaving behind a so-called proto-neutron star (PNS). As the shock wave dissipates energy while moving outward, it ultimately stalls to a so-called standing accretion shock (SAS) [2]. The shock is unstable to nonradial deformations of the shock front, resulting in large nonspherical oscillations of the shock front [3]. This instability is called the standing accretion shock instability (SASI). Even though the system shows complex nuclear, neutrino, and magnetohydrodynamical interactions, the SASI is thought to be purely hydrodynamic [3].

Two possibilities to drive the SASI have been discussed [4]: the purely acoustic cycle [5] and the advective-acoustic cycle [6]. The purely acoustic cycle is centered on the concept of acoustic waves being trapped in the postshock cavity. After being amplified at the shock, acoustic waves propagate back towards the PNS. Reflection of the acoustic waves at the PNS surface sends them back outward to the shock, therefore completing the feedback cycle of the instability [5]. In the advective-acoustic cycle, acoustic waves hitting the shock front generate perturbations in entropy and vorticity in between the shock and the PNS. These perturbations are advected in the postshock flow towards the PNS surface. Such

advected perturbations induce new acoustic waves which in turn propagate to the shock front. The accompanied perturbation at the shock front closes the feedback cycle [6].

Allowing for an intuitive and pedagogical approach of the complex astrophysical phenomena of the SASI, Foglizzo *et al.* [7] built a tabletop experiment based on the analogy between acoustic waves in a gas and surface gravity waves in shallow water. With the deformation of the water surface in a shallow water system behaving as the pressure in gas following an isentropic process, a hydraulic jump mimics the shock front of the SAS. Surface gravity waves oscillate the surface height of the water and correspond therefore to acoustic waves in the gas system. The instability is called the shallow water analog of the standing accretion shock instability (SWASI). The SWASI experiment is 10^6 times smaller and 100 times slower than its astrophysical analog, but shows dimensionless similarity [7]. To gain further insight into the driving mechanism of the SWASI and the modes present during SWASI, an experiment similar to the one described in Ref. [7] has been built. The experiment is described in Sec. II A. In the first step, the fluctuation dynamics are studied through Fourier transform profilometry (Secs. II B and III A). It will be shown that surface gravity waves preferentially propagate radially outward, which favors the advective-acoustic cycle as the driving mechanism of the SWASI (Sec. III B).

II. EXPERIMENTAL SETUP

A. Shallow water standing accretion shock experiment

Figure 1 shows the experimental setup of the shallow water accretion disk experiment (SWADEX). The central element is the water basin (a in Fig. 1). In the vertical direction, the pressure gradient is balanced by the gravitation force. Therefore, changes in the depth lead to changes in the pressure and a radial gradient in the depth profile leads to a radial gradient in the pressure. In the experiment presented here the bottom boundary H is designed to follow a gravitational potential

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FIG. 1. Computer-aided design rendering of the SWADEX. Shown are: (a) the central water basin with the boundary following a gravitational potential, (b) the upper end of the drain controlling the flow out of the pool, (c) the vertically adjustable drain pipe, and (d) the circular basin distributing the inflow of water.

$H(r) = A_0/r$ (with constant $A_0 = 1000 \text{ mm}^2$). This results in the radial pressure gradient $dp/dr > 0$ to point outward, as it is proportional to $dH/dr > 0$ in the shallow water system. The corresponding pressure force $-dp/dr < 0$ acts like a gravitational force towards the center. Due to the hyperbolic shape of the surface, the effective potential is formally analogous to the gravitational potential. The inner radius is $r_* = 25 \text{ mm}$ and the outer radius is $r_{\text{out}} = 250 \text{ mm}$ (Fig. 2). The gravitational funnel is made of aluminum.

To study the SWASI, water seeps in from the outside of the gravitational funnel. If the flow velocity exceeds the wave velocity of the surface gravity wave, a hydraulic jump develops. The radial position of the hydraulic jump depends on the depth as well as on the flow velocity. Water accumulating in the gravitational potential in the center is continuously extracted by spilling over the upper edge of a vertical pipe (b in Fig. 1). The vertical pipe can be moved in the vertical direction.

FIG. 2. Sectional drawing of the central pool including the surrounding acrylic glass basin and the baseplate at the bottom. Dimensions in the image are given in millimeters. The water cycle is indicated by the blue arrows and dotted blue lines illustrate filled water basins.

FIG. 3. Schematic drawing of the Fourier transform profilometry setup: 1 marks the projector and 2 a camera observing the surface [8].

The radial position of the hydraulic jump can be adjusted by changing the flow out of the system via the vertical position of the drain pipe.

The water cycle is indicated by the blue arrows in Fig. 2. The water leaving the basin through the drain pipe is pumped back into the annular reservoir through three hoses. The inflow of water into the annular reservoir is regulated by a ball valve. Using only three hoses is insufficient in distributing the water evenly in the reservoir basin. Flat nozzles are added to the hoses to spread the water to a larger area to achieve a more homogeneous flow into the central basin. The reservoir around the gravitational funnel consists of curved acrylic glass (d in Fig. 1 and Fig. 2). In the center of the reservoir basin a second wall of curved acrylic glass is inserted halfway from the top, forming a tunnel for the water to pass through. This setup prevents local flow perturbations induced by the inflow from the pump to propagate directly to the funnel. Dynamic pressure perturbations have to be transformed to static perturbations and back to dynamic pressure perturbations to disturb the boundary of the experiment.

B. Fourier transform profilometry

Surface gravity waves can be measured as height fluctuations of the water surface. Fourier transform profilometry (FTP) allows one to capture a two-dimensional height map of the water surface. A predefined spatially periodic pattern is projected onto the surface. Any perturbation of the surface height leads to a phase shift of this known periodic pattern at the position of the perturbation, which can be used to reconstruct the surface height. A projector and a camera are mounted above the central water basin. The water is dyed opaque white with titanium oxide to enhance the diffuse reflectivity of the water.

The general setup is shown in Fig. 3 with the projector (1) and the camera (2). The height of projector and camera above the water surface is $L = 1300 \text{ mm}$ and the distance between the camera and projector is $D = 460 \text{ mm}$.

The periodic pattern used is a sinusoidal plane wave in the y direction (Ronchi grating), described by

$$I = I_0 \sin\left(\frac{2\pi}{p}y\right). \quad (1)$$

The pattern wavelength p can be determined by means of Fourier transformation. This parameter determines the spatial resolution of height structures and should therefore be chosen as small as possible. However, p is limited by the spatial resolution of projector and camera, as well as the geometric arrangement of the setup. For the data presented in this paper, a grating size of $p = 3.238$ mm was chosen. A ViewSonic PX725HD digital projector is used to project this pattern with a resolution of 1920×1200 pixels. Data are recorded with a Ximea MQ042MG-CM camera at a resolution of 2048×2048 pixels and a frame rate of 90 Hz. Time series of 2000 frames corresponding to about 22 s are taken under stationary conditions.

Figure 3 illustrates the concept of FTP. The camera observes a point a at position $(x, y, h = 0)$ on the unperturbed surface Θ at pixel A' . The recorded intensity is set by the pixel A of the projector. If the flat surface Θ is replaced by a deformed surface Σ , the same pixel A' now records the intensity at point $b(x', y', h)$. However, the intensity at point b originates from pixel B of the projector instead of pixel A . As the intensity values across the projector pixel map are periodic in Y and defined by Eq. (1), the intensity difference between A and B can be described by a phase shift $\Delta\phi$. The height difference h between the unperturbed surface and the deformed surface, as well as the shift in x and y , δx and δy , respectively, at each pixel can be calculated from this phase shift. This process requires a reference image with intensity $I_{\text{ref}}(x, y)$, which is recorded at a completely filled pool with undisturbed water surface. This reference image is then used for the subsequent data images with intensity $I(x, y)$. By Fourier filtering the data in the y direction around the frequency of the grating, noise and artifacts from the background are suppressed. The complex output of the inverse Fourier transform after filtering carries the phase information in the imaginary part. This property can be used to extract the phase shift between the reference and data image by multiplying the intensity of the data image with the complex conjugate of the reference image. This yields the phase shift

$$\Delta\phi = \text{Im}[\ln(I I_{\text{ref}}^*)]. \quad (2)$$

The obtained phase is limited to a range from $-\pi$ to $+\pi$ and phase values exceeding this scale continue at the opposite end of it (e.g., $\Delta\phi = 3/2\pi \rightarrow \Delta\phi = -1/2\pi$), which is generally referred to as a wrapped phase. By using a phase unwrapping algorithm these shifts can be corrected and the real phase difference can be obtained. By means of triangulation the three position shifts can be calculated from the phase difference $\Delta\phi$ with [8]

$$h = \frac{\Delta\phi L}{\Delta\phi - 2\pi/pD}, \quad (3)$$

$$\delta x = \frac{x}{L}h, \quad (4)$$

$$\delta y = \frac{D-y}{L}h. \quad (5)$$

FIG. 4. An example of a standing accretion shock in the SWADEX. The water is dyed with titanium oxide to enhance the reflectivity of the surface for diagnostic purposes.

Therefore, the water surface deformation can be mapped via FTP. This enables precise observation of the phenomena present in the SWASI and yields further insight into the mechanism driving this instability.

III. RESULTS

Figure 4 shows a typical picture of the experiment where the SWASI is formed. The shock is located close to the center in Fig. 4. To allow a comparison to previous experiments [7], the characterizing dimensionless quantities of the experiment presented here will be shortly discussed. This allows us to determine the hydrodynamical regime of the data shown in this paper. By normalizing spatial distances to the jump radius r_{jp} and times to the free-fall timescale $t_{ff}^{jp} = r_{jp}/v_{ff}$ (with $v_{ff} = \sqrt{2gH^{jp}}$ the free-fall velocity) the three dimensionless parameters characterizing the SWASI can be deduced. These are the relative size of the inner boundary r_*/r_{jp} , the preshock velocity v_1/v_{ff} in units of the local free-fall velocity, and the Froude number $\text{Fr} = v/\sqrt{gh}$ [7]. The data presented in this paper were recorded for a representative run with the hydraulic jump occurring at $r_{jp} = 106.8$ mm, and thus $r_*/r_{jp} = 0.23$.

Since the jump is measured under stationary conditions, the azimuthally averaged inflow velocity v_1 ahead of the jump $r_1 \gtrsim r_{jp}$ can be determined by measuring the water flow rate Q from the drain into the basin. The flow rate Q of the setup has been determined at $(2.5 \pm 0.2) \times 10^5$ mm³/s. Assuming azimuthal symmetry and a cylinder-jacket-shaped inflow area, v_1 can be calculated as

$$v_1 = \frac{Q}{2\pi r_{jp} h_1} \quad (6)$$

with the water height $h_1 = 1.03$ mm right outside the jump at radius $r_1 \gtrsim r_{jp}$. The radial inflow velocity $v_1 = 364$ mm/s can be expressed in terms of the free-fall velocity $v_1 = 1.1v_{ff}$. The upstream Froude number can thereby be calculated as $\text{Fr}_1 = v_1/\sqrt{gh_1} = 3.6$. As shown, the experiment reported is conducted at dimensionless numbers of $r_{jp}/r_* \sim 4$, $v_1 \sim v_{ff}$, and $\text{Fr} \sim 4$ and thereby in a regime similar to that of the experiments reported in Ref. [7]. Discrepancies can be explained by

FIG. 5. (a) Raw data recorded by the SWADEX, (b) data after Fourier filtering around $k = 1.94 \text{ mm}^{-1}$, (c) wrapped phase difference between data and reference image, and (d) unwrapped phase map.

varying experiment parameters, especially the notably smaller hyperbolic shape parameter A_0 compared to Ref. [7]. The corresponding Reynolds number is about $\text{Re} = h\nu/\nu \sim 400$, when a viscosity of $\nu = 0.9 \text{ mm}^2/\text{s}$ is assumed. Influences of the TiO dye on the fluid viscosity are assumed to be small. As the Reynolds number is significantly below the critical Reynolds numbers (about 2000) of boundary-layer-induced turbulence, the radial flow is expected to be in the laminar regime.

A. Height reconstruction by FTP

In the following the procedure to obtain height profile and perturbation measurements is explained. Figure 5(a) shows the unfiltered data taken from a representative run of the experiment. The sinusoidal grating can be seen as well as the shock and the drain in the middle of the pool. As described in Sec. II B, these data are bandpass filtered around the frequency $k = 2\pi/p = 1.94 \text{ mm}^{-1}$ of the projected sinus pattern to improve the signal quality. This is done by applying a rectangular filter function with $\Delta k = 0.40 \text{ mm}^{-1}$ on the Fourier spectrum along the Y axis of Fig. 5(a). After an inverse Fourier transformation, the data such as those depicted in Fig. 5(b) are obtained. While most of the background disturbances are smoothed out, the phase shifts caused by changes in depth and the shock in the center are still visible. With the reference data from the completely filled pool, the phase difference is calculated. This phase map, however, is still wrapped (see Sec. II B), which leads to discontinuities as shown in Fig. 5(c). By applying a two-dimensional phase-unwrapping algorithm [9] it is possible to calculate the

unwrapped phase map shown in Fig. 5(d). At the position of the drain in the center of Fig. 5(d), the absolute intensity is low and artificial structures can be seen.

Equations (3)–(5) allow us to triangulate the surface height map from the measured phase shift data. In Fig. 6 the surface of the shallow water is shown. It can be seen that in the outer radial region, the water surface follows the $1/r$ profile of the pool. In the vicinity of the jump, slight perturbations of the surface are visible.

To extract the shock profile, the shape of the pool is measured without a shock. This is achieved by the same procedure as described above, but with the central drain completely withdrawn so the water is not able to accumulate. Subtracting the thereby obtained height map from the one obtained in Fig. 6 gives the surface of the shock (Fig. 7). A clear elevation can

FIG. 6. Surface of the shallow water.

FIG. 7. Shock profile obtained by subtracting the depth profile.

be observed close to the center. This elevation is disturbed by a crescent-shaped perturbation. Changing to polar coordinates and averaging over the azimuthal angle gives the radial profile of the height (Fig. 8). Outside of $r > 106.8$ mm the profile is constant until the pool depth becomes too low and therefore decreases the shallow water height; inside $r < 106.8$ mm the height steepens up. The height of the hydraulic jump is about 1.5 mm, taking an upstream height of $h_1 = 1$ mm and a downstream height of $h_2 = 2.5$ mm. The expected height amplification for an ideal rectangular jump $h_2/h_1 = 0.5(\sqrt{1 + 8\text{Fr}^2} - 1)$ is about 4.6 for a Froude number of 3.6. We would expect a height of $h_2 = 4.6$ mm for $h_1 = 1$ mm or $h_1 = 0.5$ mm for $h_2 = 2.5$ mm. The inconsistency between the estimation of $\frac{h_2}{h_1}$ and the Froude number Fr points to a nonideal hydraulic jump formula due to a significant loss of radial momentum. Due to the $v_{ff} \sim 1$, strong impact due to friction is not expected. However, as the jump is accompanied by a flow shear, this leads to a finite radial-azimuthal Reynolds stress, which leads to reduced radial momentum by transfer of radial to azimuthal momentum. The momentum balance should be studied in detail in the future.

FIG. 8. Time and azimuthally averaged radial profile of the surface height of the hydraulic jump. The water is drained at $r < r_{in} = 26$ mm. The zero line is chosen arbitrarily.

FIG. 9. Dispersion relation for low azimuthal mode numbers. The power of intensity (in arb. units) is shown in a linear representation.

B. Dispersion relations

At azimuthal mode numbers of $l = 1$ and 2 the SWASI shows the highest growth rates. By applying a Fourier transform in the azimuthal direction ($\theta \rightarrow k_\theta$) the wave-number spectrum is analyzed in more detail. An additional Fourier transform of the time coordinate ($t \rightarrow \omega$) yields the dispersion relation $\omega(k_\theta)$. The azimuthal mode number l is related to the azimuthal wave number by $k_\theta = l/r$. Figure 9 shows the l - f power spectrum at low l of surface height fluctuations in the outer region of the hydraulic jump $91.4 < r < 97.1$ (r in units of mm^{-1}). The lowest wave numbers ($l = -1, 1, 2$) exhibit the strongest fluctuations. The most dominant contribution is found at $l = 1$ and $f = 0.45$ Hz. This represents the dominant mode of the SWASI.

The dominance of the $l = 1$ mode can also be seen by measuring the jump radius r_{jp} at different azimuthal angles $-\pi < \theta < \pi$ in Fig. 10. The strongest contributions to the jump radius are found from the azimuthal mode numbers of $l = 1$ and 4, contributing about 14.9% and 4.6% of the total spectral power, respectively. The $l = 1$ mode is shown as a sinusoidal fit (orange) in Fig. 10. Due to the varying shape of

FIG. 10. Radial position of the jump r_{jp} (blue) along the azimuthal angle θ . The dominant $l = 1$ mode (orange) and the deformation amplitude $\Delta r = 4.4$ mm are determined by a sinusoidal fit.

FIG. 11. Plot of the k_θ - f spectrum between $r = 91.4$ mm and $r = 97.1$ mm. The power of intensity (in arb. units) is shown in a logarithmic representation. The red lines indicate the dispersion of surface gravity waves.

the hydraulic jump, it is not possible to determine a clear edge for all azimuthal angles, leading to occasional discontinuities (see Fig. 10). The amplitude of the shock deformation is $\Delta r = 4.42 \pm 0.08$ mm. The data are obtained by averaging over 22 s and the asymmetric structure is stationary and not propagating.

In the following perturbations at smaller scales are investigated. The dispersion relation of shallow water gravity waves is given by

$$\omega = \sqrt{gh_0}k_\theta. \quad (7)$$

The azimuthal wave-number–frequency (k_θ - f) power spectrum is shown in Fig. 11. The red lines show the dispersion relation of shallow water surface gravity waves. The smallest azimuthal wave number k_θ in Fig. 11 corresponds to the $l = 1$ mode number observed in Fig. 9. Fluctuation activity associated with shallow water surface gravity waves is observed within $-0.1 < k_\theta < +0.2$ (k_θ in units mm^{-1}) below 3 Hz. The power is not equally distributed between both directions of propagation; more power is found for positive k_θ . A detailed investigation of the symmetry breaking in k_θ however is beyond the scope of the present study.

One main difference between the advective-acoustic cycle and the purely acoustic cycle is the symmetry of power in radial propagation. In the purely acoustic cycle acoustic waves propagate from the PNS to the shock, where they are amplified. Then the acoustic waves propagate back to the PNS. If there is any asymmetry in power, the waves propagating radially inward from the shock to the PNS should be stronger. In the case of the advective-acoustic cycle, acoustic waves propagate to the shock, where entropy-vorticity waves are generated. These propagate back to the PNS and excite acoustic waves propagating towards the shock. Therefore, there is more power in outward propagation in the case of the advective-acoustic cycle.

Pressure fluctuations can be separated into acoustic pressure (sound) and the hydrodynamic pressure (pseudosound) perturbations. Acoustic pressure fluctuations propagate and

FIG. 12. Plot of the k_r - f spectrum from $r = 42.8$ mm to $r = 114.2$ mm. The power of intensity (in arb. units) is shown in a logarithmic representation.

are governed by a linear dispersion relation. Pseudosound is weakly influenced by compressibility and rather related to vorticity. The structures do not propagate much. As we are interested in the power asymmetry of the acoustic pressure fluctuations only, we should interpret only fluctuations with a frequency higher than and close to the speed of sound $f \gtrsim c_s k$ as propagating acoustic waves. In the shallow water experiment acoustic waves correspond to shallow water gravity waves.

The radial shallow water gravity wave dispersion is $f = \frac{1}{2\pi} \sqrt{gh_0}k_r$. The radial variations in the height have to be taken into account. The depth is varying with the radius $h_0(r)$. Within a given radial region $r = r_0 \pm \Delta r$, the frequency observed within cones is given by

$$f = \frac{1}{2\pi} \sqrt{gh_0(r_0 \pm \Delta r)}k_r. \quad (8)$$

In Fig. 12 the radial dispersion relation is shown. The red lines indicate the predicted range of shallow water gravity waves. The fluctuations close to the red line are in agreement with shallow water gravity waves. Shallow water surface gravity waves are observed for frequencies below 8 Hz and $k_r < 0.6 \text{ mm}^{-1}$. The clearest contribution is around $k_r = 0.25 \text{ mm}^{-1}$ and $f = 5$ Hz. These fluctuations are bit above the red line and can be seen as acoustic pressure fluctuations with respect to the SASI. These waves are propagating radially outward, which indicates the possibility of the advective-acoustic cycle in these experiments. A pure acoustic cycle is not in agreement with the measurements. For the pure acoustic cycle, stronger amplitude for waves propagating radially inward are expected, since the acoustic waves are amplified at the shock.

It is worth noting that at the frequency of $f = 0.45$ Hz, associated with the $l = 1$ mode of the SWASI (Fig. 9), the dominant contribution from the radial wave number is found at $k_r = 0.06 \text{ mm}^{-1}$. This mode is below the red line, which can be interpreted as pseudosound. Indeed, the mode is not propagating radially. Instead the radial wave number can be related to the radial extent of the hydraulic jump

$\Delta r_{jp} = 25$ mm (Fig. 8) by $k_r = \pi/2\Delta r_{jp} = 0.06$ mm⁻¹. The mode at $l = 1$, $k_r = \pi/\Delta r_{jp}$, and $f = 0.45$ Hz is responsible for the characteristic sloshing and spiraling dynamics of the SWASI itself.

IV. CONCLUSION

Experiments as proposed in Ref. [7] allow us to study instabilities and turbulence in accretion disk geometry. Such an experiment has been built and as a first application the fluctuation dynamics in the radial direction during a standing accretion shock have been studied in this shallow water accretion disk experiment. A Fourier transform profilometry diagnostic has been set up to globally measure the height with high precision. This allowed us to measure zonally averaged height profiles and their local perturbations. The shallow water analog to the standing accretion shock instability is dominated by low azimuthal mode numbers, in particular $l = 1$. During SWASI the perturbations of the surface height can be described by shallow water surface gravity waves. The shallow water surface gravity waves preferen-

tially propagate radially outward, which is consistent with an advective-acoustic-like amplification cycle for the SWASI. Whether the observed shallow water surface gravity waves are the cause or the consequence of the SWASI needs additional time-dependent analysis, which is left for future conditional averaging and/or wavelet analysis.

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