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Unique Aggregations of a Large Undescribed Solitary Tunicate in the Arabian Sea

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Abstract: We document aggregations of an undescribed benthic solitary tunicate of the family Pyuridae from the Arabian Sea. This new genus was found forming dense thickets in shallow rocky substrates around Masirah Island and the Dhofar area in Oman. Such aggregations of tunicates have not been reported before from coral reefs in the Indo-West Pacific region and the Atlantic. This observation contributes to our understanding of the ecology and biogeography of ascidians, setting the stage for a comprehensive species description and in-depth analysis of this species.

Keywords: Indian Ocean; Masirah Island; Ascidiacea; Oman; phylogeny; anatomy

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The Arabian Sea in the northwest Indian Ocean has a unique hydrography and climate conditions, predominantly influenced by the seasonal monsoons. The summer monsoon causes mixing of waters, whereas the winter monsoon triggers upwelling [1,2]. These phenomena together with bottom topography and consistent eddies [3], contribute to the productivity of these waters and create a diverse ecosystem with endemic biota along the Omani coastline, distinct from the neighbouring Red Sea and Persian Gulf [4,5]. The Omani waters are further differentiated between the Sea of Oman and the Arabian Sea coasts by one of the steepest marine environmental and biogeographic breaks at Ras al Hadd [6]. The Arabian Sea coast holds further heterogeneity because of variation in geomorphology, exposure, and upwelling, promoting habitat and faunal differentiation.

A distinct sub-region along the Arabian Coast is represented by Masirah Island, surrounded by nutrient-rich waters rising off the southern parts of the island during the southwest monsoon [7], and persistent eddies between the island and Ras Madrakah [8]. Mixed tides with 3 m fluctuation cause strong alongshore currents affecting the shallow zones of the island, especially at its northern and southern ends (Figure 1). The island has a perfect geographical position for comparative study of upwelling, productivity of the pelagic ecosystem, and monsoon winds [2].

During a large-scale marine biodiversity survey off the coast of Oman (2019–2023) that aimed to explore its macroinvertebrate fauna, we encountered dense aggregations and thickets of giant solitary tunicates at depths of 2–15 m (Figures 2–4). The animals were up to 20 cm in diameter, with a tunic of about 3–4 cm in thickness (Figure 3F). They were attached to rocks and artificial structures (wrecks) in monospecific aggregations across

hundreds of square meters, with densities of several dozen per square meter in places (Figure 2, Video S1). Animals were densely packed, attached to each other, and adhering strongly to the bottom. They were lined up like cannonballs, forming a unique visual landscape (Figure 2A; Video S1).

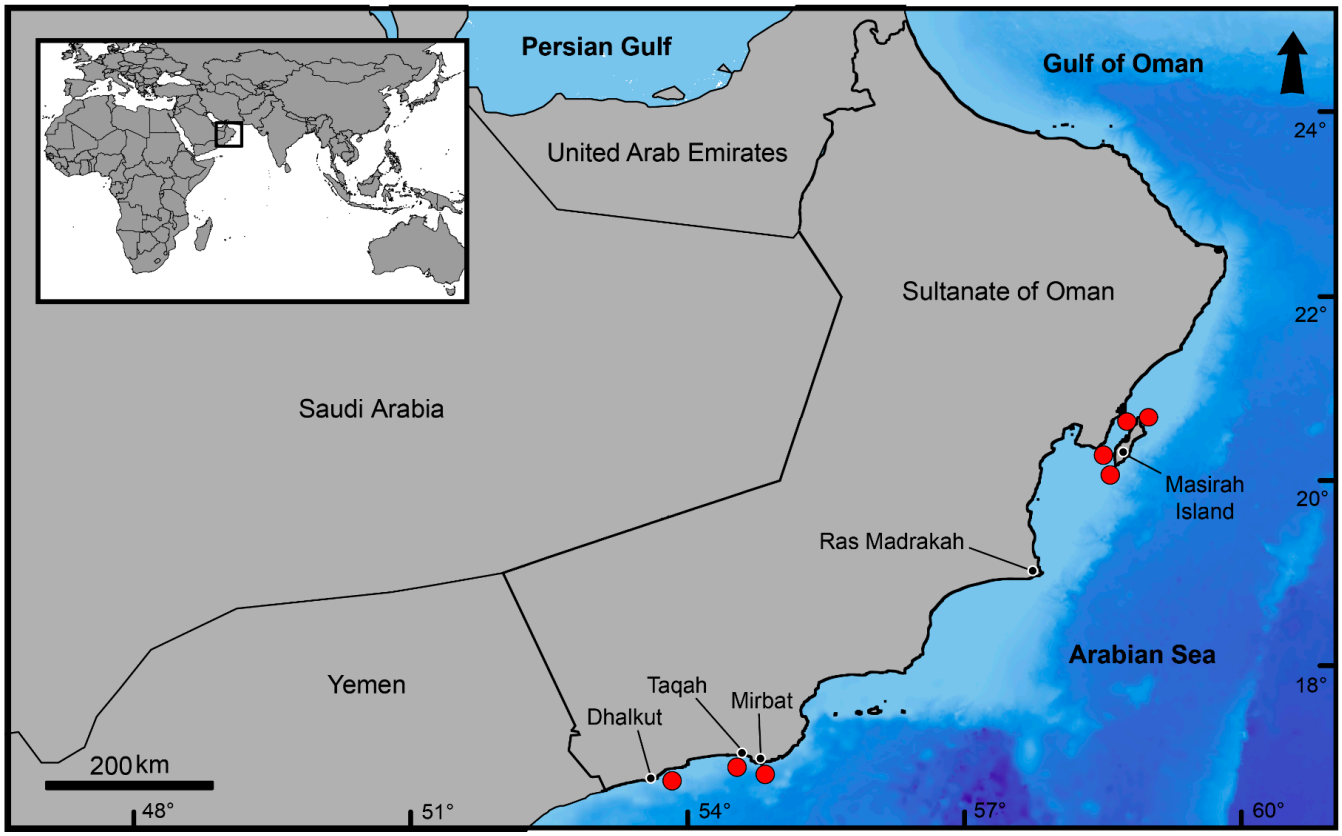

Figure 1. Locations where the undescribed pyurid tunicate species was observed along the Omani coast and around Masirah Island (red dots). Blue shading represents depth gradients.

At most locations, a notable proportion of these ascidians were broken open, with their bodies gone and only partial shells of their thick tunic remaining (Figure 3A–D). Empty tunic shells were common, both adhering to the substratum as well as loosely settled in the vicinity of live animals. These appear to represent predation by a durophagous predator, likely sea turtles, tetraodontiform fishes, or the giant hogfish, *Bodianus macrognathos*, as all have been observed in the area. The abundance of these remains suggests high levels of predation as well as a rapid growth of the ascidians to sustain this level of mortality.

The exposed tunics had an epibiont community dominated by turf and crustose coralline algae and sponges (Figures 2 and 3A–D). As of yet, no internal symbionts, such as shrimps and pea crabs were observed in the dissected individuals, as expected from literature on the associated fauna of tunicates [9–11].

The observed species was encountered in two types of habitats characterized by high flow, typically in large aggregations. It was common at the northern and southern ends of Masirah Island, where intense tidal currents drain the shallow isthmus between the island and the mainland. It was also common in shallow (2–6 m) surge channels in Mirbat and Dhalkut (Dhofar Governorate), washed by wave-driven currents. The species was also found to foul man-made structures and intake pipes in Taqah, again in a high-flow setting. These observations suggest that gigantism and abundance of this species may be driven by a combination of the high productivity of this area combined with high flow delivering food to these sessile filter feeders. The observed range of this species, from Masirah to Dhalkut, is similar to numerous other Omani endemics that characterize this upwelling zone [4,6,12].

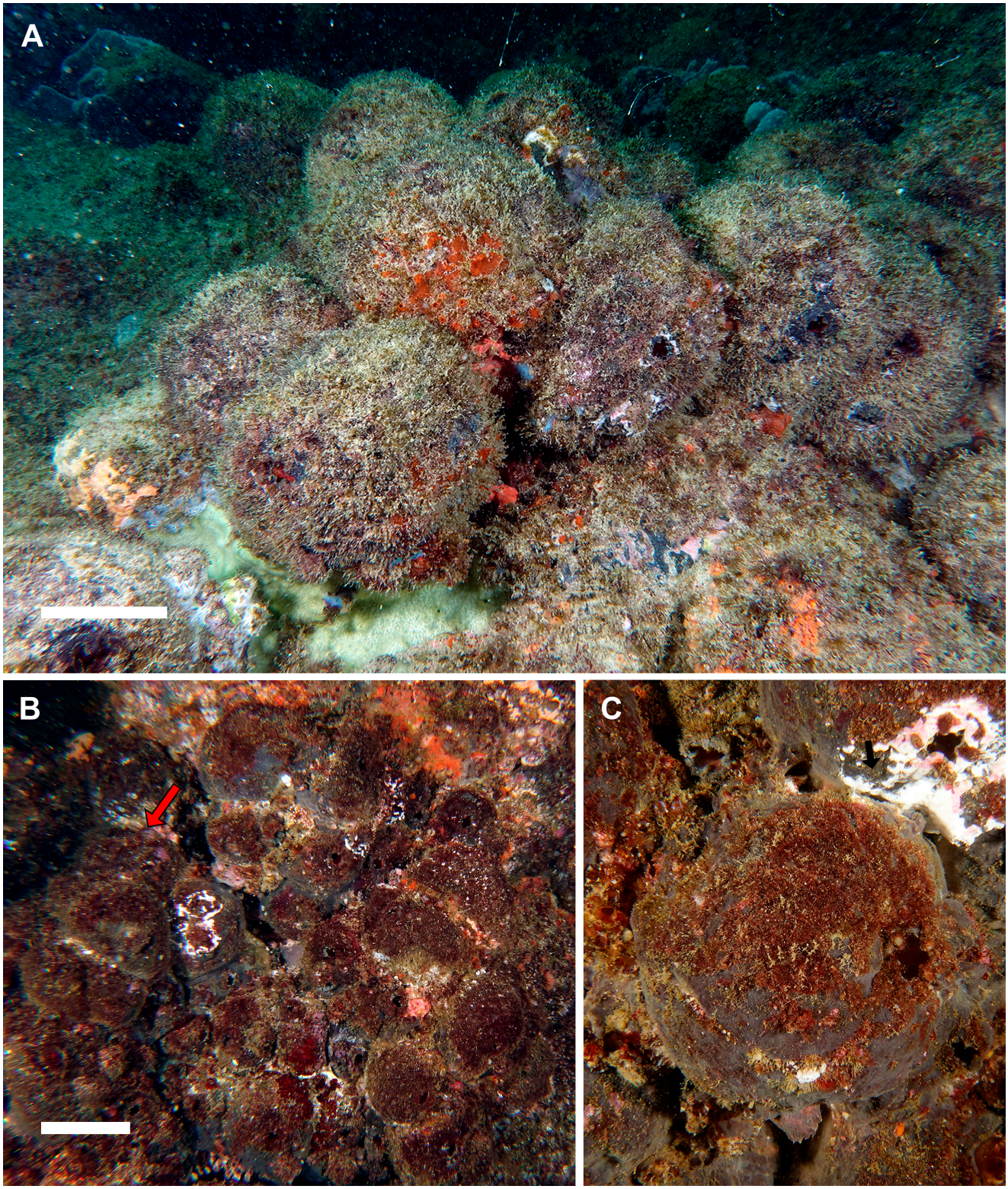

Figure 2. Dense aggregations of the undescribed pyurid tunicate species around Masirah Island, Oman. Scales = 10 cm. Note overgrowth by other organisms. (**A**) Individuals at the north of the island at 5 m depth. (**B**) Individuals at the southwest of the island at 10 m depth. (**C**) Close-up of an individual animal.

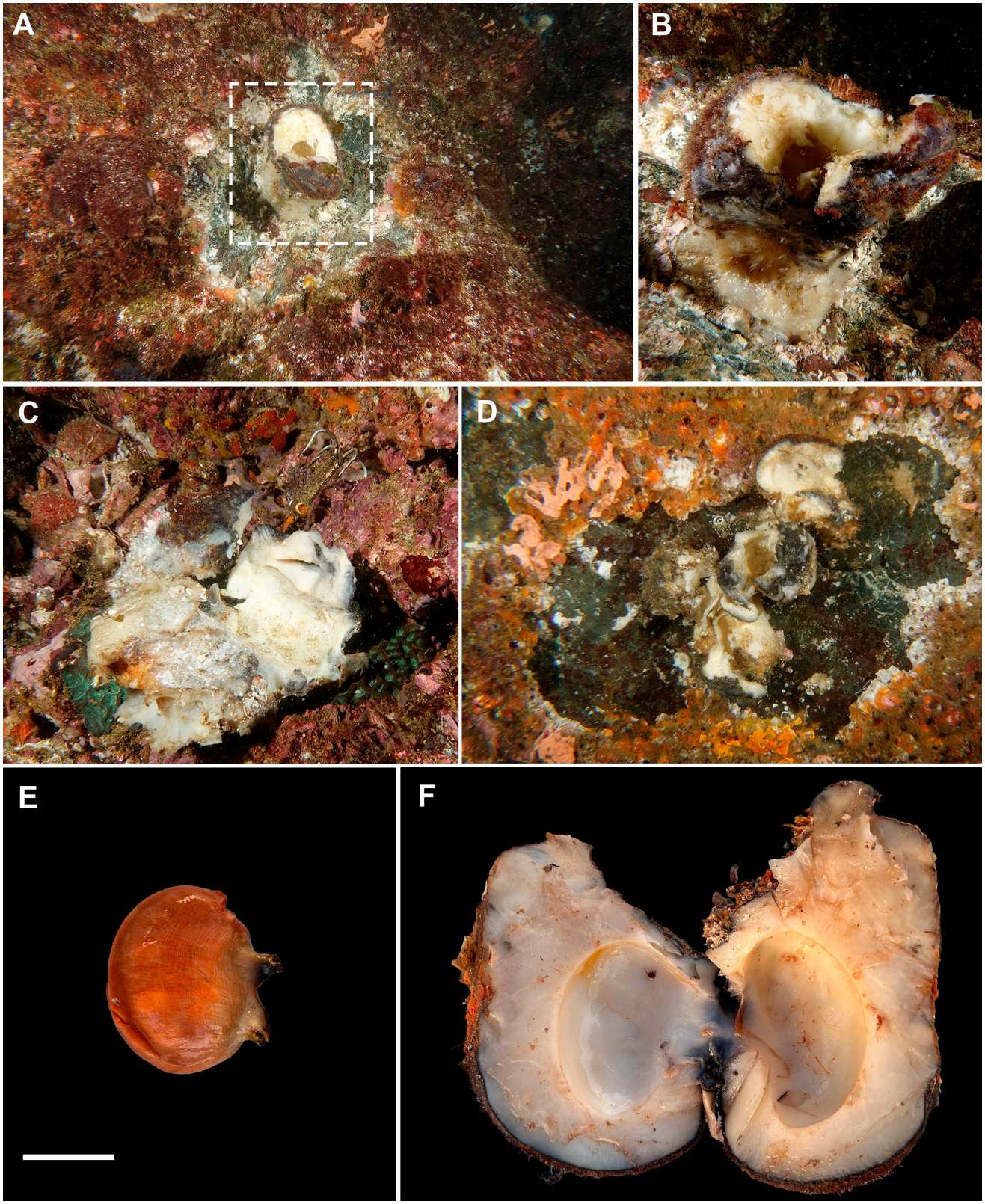

Figure 3. (**A**,**B**) Tunic remaining from individual attached by putative predator; note the absence of the orange tunicate body and remaining white tunic (hatched rectangle). (**C**) Remnant of an individual, most likely removed by predation. (**D**) Space left on rock by several individuals that appear to have been recently removed judging by the clean, vacant surface. (**E**) The individual without its thick tunic. (**F**) Cross-section of the individual with the body separated, scale = 5 cm.

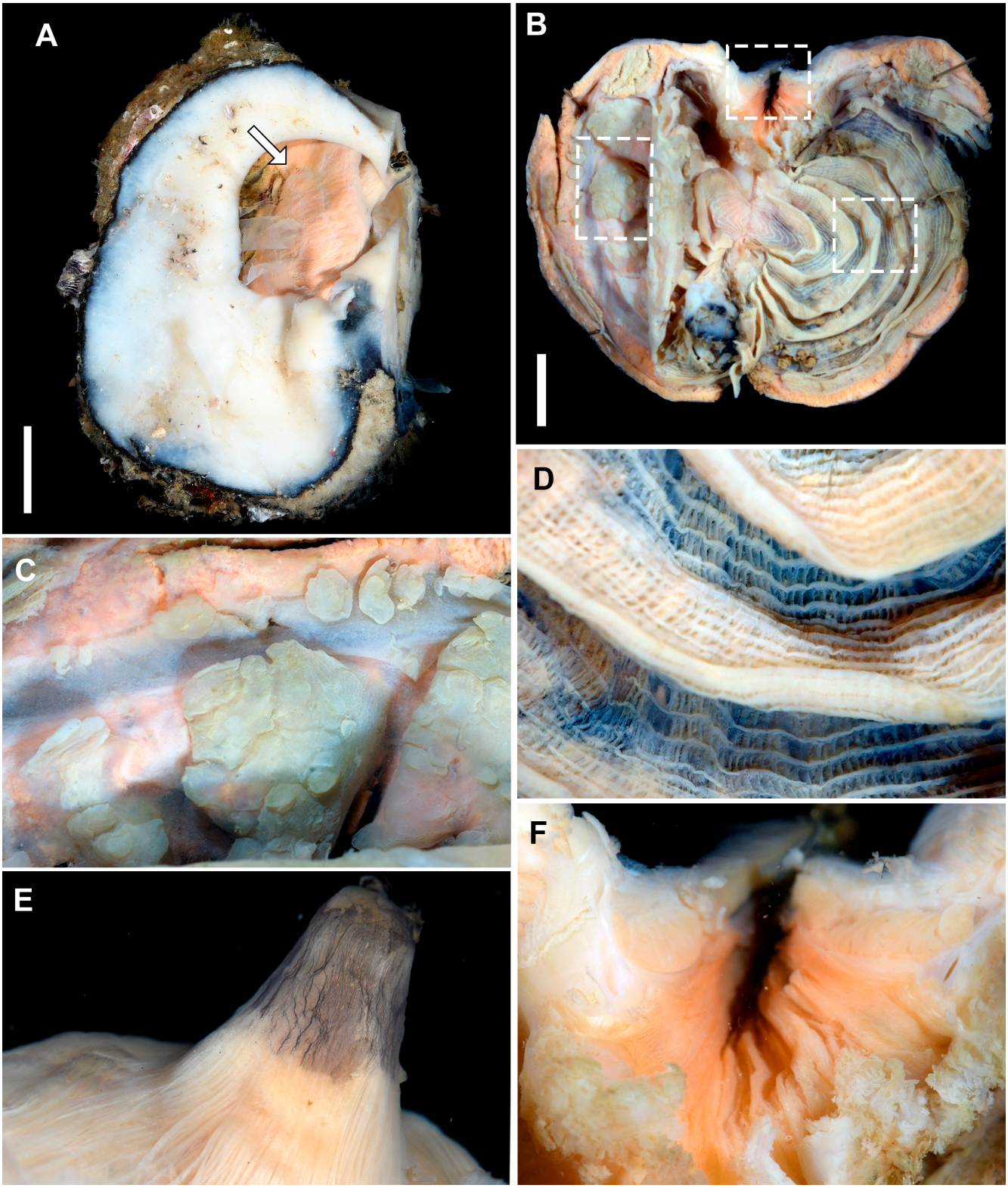

Figure 4. Anatomical section of the preserved specimen of the undescribed pyurid tunicate species from Oman. (**A**) Cross-section of the individual, arrow pointing at the body wall, scale = 2 cm. (**B**) Dissected pharynx and body, hatched rectangles, representing (**C**–**F**) macro images, scale = 1 cm. (**C**) Endocarps. (**D**) Pharynx wall with folds, showing longitudinal vessels and 2nd, 3rd, and 4th folds. (**E**) External view of the oral siphon and oral tentacles. (**F**) Internal view of the oral siphon and oral tentacles.

Several specimens were vouchered in the Florida Museum (UF Chordata 3426, 3427, 3436, 3448, 3449, 3450), and Smithsonian National Museum of Natural History (USNM 1707100, USNM 1707101). Initial assessment based on morphology (Figures 3E–F and 4) and mitochondrial *Cytochrome c Oxidase subunit I* (*COI*) sequences (Figure S1) suggest that this species represents an undescribed genus of the family Pyuridae Hartmeyer, 1908. This family of solitary ascidian has a global distribution [13,14], with 16 genera [15].

While about 3000 extant species of ascidians have been described worldwide [14], inhabiting all marine habitats with greatest abundance and diversity in shallow coastal waters, the group remains understudied, especially in the tropics. Most of the shallow-water ascidian records from the Arabian region are from the Red Sea [16–18], with few additional records from other areas of the Arabian Peninsula [19–21]. The species reported here was first encountered during the "Ardoukoba" expedition to Masirah Island in 1999, and reported as *Microcosmus* Heller, 1877 by Méliane and Ramos-Esplá [21], but no subsequent observations were ever made on its distribution and identity.

The convergence of abundant food resources, optimum environmental conditions, reproduction and feeding strategies of the species has led to robust and dense populations of the undescribed tunicate in our surveyed area. The high biomass of ascidians is expected in eutrophic waters due to their efficient filter feeding strategy [22]. Additionally, the pyurid ascidians rely only on sexual reproduction [23], which is closely influenced by environmental factors, mainly the temperature, and chlorophyll-a in the water column [24]. Therefore, in optimum environments, they can form aggregations, colonize man-made structures, and become potential bio-invaders [23,25]. Our observations can be largely explained by the region's topography and hydrographic regimes, a direct consequence of the seasonal monsoons, together with strong local tidal currents around the island that enhance nutrient availability.

This discovery contributes to our understanding of the biodiversity of the Arabian Sea marine fauna, highlighting the unique environmental conditions and the high endemicity of this area. Future research will focus on formally describing the new taxon.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/d16040221/s1, Video S1: Underwater video from Masirah Island; Figure S1: Phylogenetic tree of the undescribed pyurid tunicate species, edited on iTOL [26], based on sequences of Cytochrome Oxydase subunit I. All other sequences were obtained from Genbank, and accession codes are indicated in the terminals, along with the genera for each used sequence. Sequences were trimmed on UGENE and aligned with the use of MAFFT and a Maximum Likelihood reconstruction using RaxML with 1000 bootstrap replicates on CIPRES [27], using GTR + G model. DNA amplified for Folmer region of *COI* with John Geller primers [28].

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References

1. Smith, S.L. Understanding the Arabian Sea: Reflections on the 1994–1996 Arabian Sea Expedition. *Deep. Sea Res. Part II Top. Stud. Oceanogr.* **2001**, *48*, 1385–1402. [CrossRef]
2. Smith, S.L.; Criales, M.M.; Schack, C. The large-bodied copepods off Masirah Island, Oman: An investigation of Southwest Monsoon onset and die-off. *J. Mar. Syst.* **2020**, *204*, 103289. [CrossRef]
3. Flagg, C.N.; Kim, H.-S. Upper ocean currents in the northern Arabian Sea from shipboard ADCP measurements collected during the 1994–1996 U.S. JGOFS and ONR programs. *Deep. Sea Res. Part II Top. Stud. Oceanogr.* **1998**, *45*, 1917–1959. [CrossRef]
4. Sheppard, C.R.C.; Sheppard, A.L.S. Fauna of Saudi Arabia. In *Corals and Coral Communities of Arabia*; Natural History Museum: Basle, Switzerland, 1991; Volume 12, pp. 3–170.
5. Obura, D. The diversity and biogeography of western Indian Ocean reef-building corals. *PLoS ONE* **2012**, *7*, e45013. [CrossRef] [PubMed]
6. Schils, T.; Wilson, S.C. Temperature threshold as a biogeographic barrier in northern Indian ocean macroalgae. *J. Phycol.* **2006**, *42*, 749–756. [CrossRef]
7. Manghnani, V.; Morrison, J.M.; Hopkins, T.S.; Böhm, E. Advection of upwelled waters in the form of plumes off Oman during the Southwest Monsoon. *Deep. Sea Res. Part II Top. Stud. Oceanogr.* **1998**, *45*, 2027–2052. [CrossRef]
8. Elliott, A.J.; Savidge, G. Some features of the upwelling off Oman. *J. Mar. Res.* **1990**, *48*, 319–333. [CrossRef]
9. Horká, I.; De Grave, S.; Fransen, C.H.J.M.; Petrusek, A.; Duriš, Z. Multiple host switching events shape the evolution of symbiotic palaemonid shrimps (Crustacea: Decapoda). *Sci. Rep.* **2016**, *6*, 26486. [CrossRef]
10. de Gier, W.; Becker, C. A review of the ecomorphology of pinnotherine pea crabs (Brachyura: Pinnotheridae), with an updated list of symbiont-host associations. *Diversity* **2020**, *12*, 431. [CrossRef]
11. De Gier, W.; Groenhof, M.; Fransen, C.H.J.M. Coming out of your shell or crawling back in: Multiple interphylum host switching events within a clade of bivalve- and ascidian-associated shrimps (Caridea: Palaemonidae). *Contrib. Zool.* **2022**, *91*, 166–198. [CrossRef]
12. Burt, J.A.; Feary, D.A.; Bauman, A.G.; Usseglio, P.; Cavalcante, G.H.; Sale, P.F. Biogeographic patterns of reef fish community structure in the northeastern Arabian Peninsula. *ICES J. Mar. Sci.* **2011**, *68*, 1875–1883. [CrossRef]
13. Pérez-Portela, R.; Bishop, J.D.D.; Davis, A.R.; Turon, X. Phylogeny of the families Pyuridae and Styelidae (Stolidobranchiata, Ascidiacea) inferred from mitochondrial and nuclear DNA sequences. *Mol. Phylogenet. Evol.* **2009**, *50*, 560–570. [CrossRef] [PubMed]
14. Shenkar, N.; Swalla, B.J. Global diversity of Ascidiacea. *PLoS ONE* **2011**, *6*, e20657. [CrossRef] [PubMed]
15. Shenkar, N.; Gittenberger, A.; Lambert, G.; Rius, M.; Moreira da Rocha, R.; Swalla, B.J.; Turon, X. 2024 Ascidiacea World Database. Pyuridae Hartmeyer, 1908. World Register of Marine Species. Available online: https://www.marinespecies.org/aphia.php?p=taxdetails&id=103449 (accessed on 5 March 2024).
16. Savigny, J.C. *Memoires Sur Des Animaux sans Vertebres*; G. Dufour: Paris, France, 1816; 240p.
17. Michaelsen, W.; Michaelsen, W. Ascidiae Ptychobranchiae und Diktyobranchiae des Roten Meeres. *Denkschr. Akad. Wiss. Wien Math. Nat. Kl.* **1918**, *95*, 1–120.
18. Michaelsen, J.W. Ascidiae Krikobranchiae des Roten Meeres: Clavelinidae und Synoicidae. *Denkschr. Akad. Wiss. Wien Math. Nat. Kl.* **1921**, *97*, 1–38.
19. Kott, P. *The John Murray Expedition, 1933–34: Scientific Reports. The Sessile Tunicata*; British Museum: London, UK, 1957; Volume 10, pp. 129–149.
20. Monniot, C.; Monniot, F. Records of ascidians from Bahrain, Arabian Gulf with three new species. *J. Nat. Hist.* **1997**, *31*, 1623–1643. [CrossRef]
21. Meliane, I.; Ramos-Esplá, A.A. Records of Ascidians (Chordata, Tunicata) from Oman, Southeast of Arabian Peninsula. In *Proceedings of the International Conference on Fisheries, Aquaculture and Environment in the NW Indian Ocean, Sultan Qaboos University, Oman, 2001*; Claereboudt, M., Goddard, S., AI-Oufi, H., Mcilwain, J., Eds.; Sultan Qaboos University: Muscat, Oman, 2001; pp. 37–43.
22. Petersen, J.K.; Riisgård, H.U. Filtration capacity of the ascidian *Ciona intestinalis* and its grazing impact in a shallow fjord. *Mar. Ecol. Prog. Ser.* **1992**, *88*, 9–17. [CrossRef]
23. Rius, M.; Turon, X.; Ordóñez, V.; Pascual, M. Tracking invasion histories in the sea: Facing complex scenarios using multilocus data. *PLoS ONE* **2012**, *7*, e35815. [CrossRef] [PubMed]
24. Nagar, L.; Shenkar, N. Temperature and salinity sensitivity of the invasive ascidian *Microcosmus exasperatus* Heller, 1878. *Aquat. Invasions* **2016**, *11*, 33–43. [CrossRef]

25. Rius, M.; Teske, P.R. A revision of the *Pyura stolonifera* species complex (Tunicata, Ascidiacea), with a description of a new species from Australia. *Zootaxa* **2011**, *2754*, 27–40. [CrossRef]
26. Ciccarelli, F.D.; Doerks, T.; von Mering, C.; Creevey, C.J.; Snel, B.; Bork, P. Phylogeny tree for the undescribed taxon. *Science* **2006**, *311*, 1283–1287. [CrossRef] [PubMed]
27. Miller, M.A.; Pfeiffer, W.; Schwartz, T. Creating the CIPRES Science Gateway for inference of large phylogenetic trees. In Proceedings of the Gateway Computing Environments Workshop (GCE), New Orleans, LA, USA, 14 November 2010; pp. 1–8. [CrossRef]
28. Geller, J.; Meyer, C.; Parker, M.; Hawk, H. Redesign of PCR primers for mitochondrial cytochrome c oxidase subunit I for marine invertebrates and application in all-taxa biotic surveys. *Mol. Ecol. Resour.* **2013**, *12*, 851–861. [CrossRef] [PubMed]