

Siphonophore Phylogeny

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Abstract

Introduction

Siphonophores are a group of 188 valid species within Hydrozoa (Cnidaria), the vast majority of which are members of the plankton (fig. 1). Siphonophores are colonial, and are composed of zooids that are each homologous to solitary animals, but are physiologically integrated (Totton and Bargmann 1965; Mackie et al. 1988; Dunn and Wagner 2006). Siphonophores differ significantly from all other colonial hydrozoans in terms of colony structure, development, and the degree to which they are functionally specialized (Beklemishev 1969; Cartwright and Nawrocki 2010). A siphonophore colony arises from a single embryo, which forms a protozooid and a growth zone from which other genetically identical zooids bud asexually (Carré 1967, 1969; Carré and Carré 1991, 1995). Each zooid arises in the same repeating species-specific pattern, and is functionally specialized for a particular task (e.g feeding, reproducing, swimming) (fig. 2) (Dunn and Wagner 2006).

Most siphonophores are planktonic, with the exception of one pleustonic species (*Physalia physalis*, Portuguese man of war) that lives at the interface of water and air, and a small clade of benthic siphonophores, the Rhodaliidae (Pugh 1983;).

Methods

This manuscript is an executable document computed directly from the data, providing an explicit and reproducible description of all findings. All scripts for the analyses are available in a git repository at https://github.com/caseywdunn/siphonophore_phylogeny_2017. The most recent commit at the time of the analysis presented here was 9202db40731b9e2c992692a0bad29e4b16ee14b9.

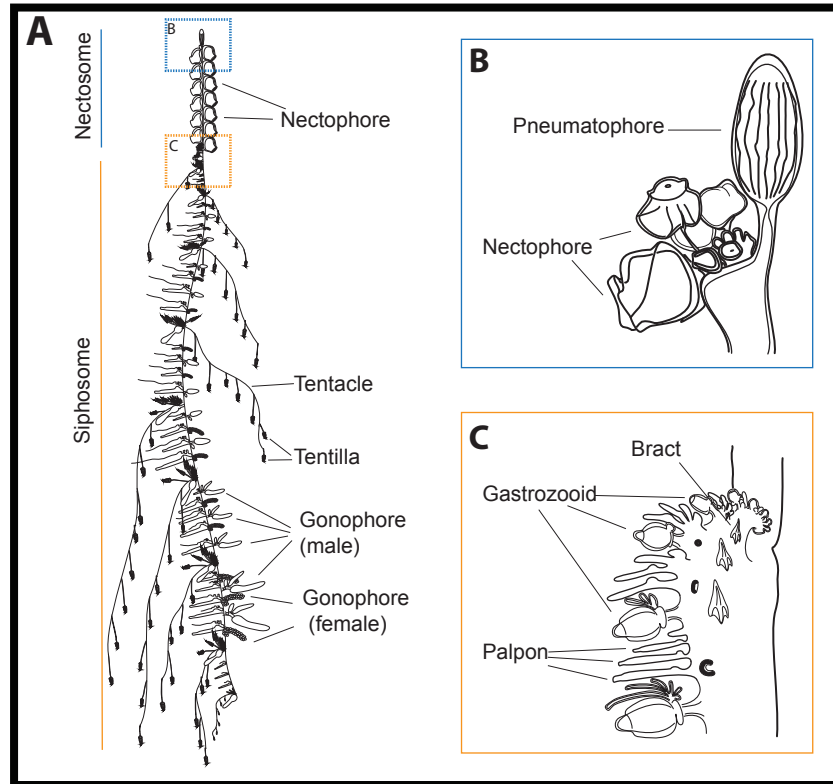


Figure 1: Schematic of the siphonophore *Nanomia bijuga*, oriented with the anterior of the colony at the top, and the ventral side to the left. Adapted from http://commons.wikimedia.org/wiki/File:Nanomia_bijuga_whole_animal_and_growth_zones.svg, drawn by Freya Goetz. (A) Overview of the whole mature colony. (B) Inset of the nectosomal growth zone with pneumatophore. A series of buds gives rise to nectophores. (C) Inset of the siphosomal growth zone. Probuds subdivide to give rise to zooids in repeating-units (cormidia). Cormidial boundaries are marked by a gastrozoid.

Collecting

Collection data on all examined specimens, a description of the tissue that was sampled from the colony, collection mode, sample processing details, mRNA extraction methods, sequencing library preparation methods and sequencing details are summarized in supplementary table 1. Monterey Bay and Gulf of California specimens were collected by remotely operated underwater vehicle (ROV) or during blue-water scuba dives. *Chelophyes appendiculata* and *Hippopodius hippopus* specimens were collected in the bay of Villefranche-sur-Mer, France, during a plankton trawl on 04/13/11. Available physical vouchers have been deposited at the Museum of Comparative Zoology (Harvard University), Cambridge, MA, or had been previously deposited at the United States National Museum (Smithsonian Institution), Washington, DC. Accession numbers are given in supplementary table X. In cases where physical vouchers were unavailable we provide photographs to document species identity (table x).

Sequencing

When possible specimens were starved overnight in filtered seawater at temperatures close to ambient water temperatures at the time point of specimen collection (supplementary table 1). mRNA was extracted directly from tissue using a variety of methods (supplementary table x): Magnetic mRNA Isolation Kit (NEB, #S1550S), Invitrogen Dynabeads mRNA Direct Kit (Ambion, #61011), Zymo Quick RNA MicroPrep (Zymo #R1050), or from total RNA after Trizol (Ambion, #15596026) extraction and through purification using Dynabeads mRNA Purification Kit (Ambion, #61006)- in case of anticipated very small total RNA quantities, only a single round of bead purification was performed; or Trizol directly into the Illumina TruSeq Stranded Library Kit. Extractions were performed according to the manufacturer’s instruction. Any resulting higher rRNA read counts were dealt with further downstream in the bioinformatics workflow. Libraries were prepared for sequencing using the Illumina TruSeq RNA Sample Prep Kit (Illumina, #FC-122-1001, #FC-122-1002), the Illumina TruSeq Stranded Library Prep Kit (Illumina, #RS-122-2101) or the NEBNext RNA Sample Prep Master Mix Set (NEB, #E6110S). We collected long read paired end Illumina data for *de novo* transcriptome assembly. In the case of large tissue inputs, libraries were sequenced separately for each tissue, subsequently subsampled and pooled *in silico*. Libraries were sequenced on the HiSeq 2000, 2500, and 3000 sequencing platforms (supplementary table 1). Summary statistics for expression libraries are given in Table 1.

Analysis

New data were analysed in conjunction with 13 publically available datasets, with a total number of 43 species. Sequence assembly, annotation, Maximum Likelihood (ML) phylogenetic analysis were conducted with the tool Agalma (Dunn et al. 2013), v. 1.00, and Bayesian Inference (BI) analyses were conducted using Phylobayes(Lartillot et al. 2009) v. 1.7a-mpi. Source code for all analysis steps, sequence alignments, sampled and consensus trees, and voucher information are available in a git repository https://github.com/caseywdunn/siphonophore_phylogeny_2017.

In the final analyses, we sampled 1,071 genes to generate a supermatrix with 60% occupancy and a length of 378,468 amino acids. Two outgroup species, *Atolla vanhoeffeni* and *Aegina citrea*, were removed from the final supermatrix and phylogeny due to low gene occupancy (gene sampling of 20.8% and 14.5% respectively in a 50% occupancy matrix with 2,203 genes). ML analyses were conducted on the unpartitioned supermatrix using the WAG+ Γ model of amino acid substitution, and bootstrap values were estimated using 1000 replicates. BI was conducted using two different CAT models, CAT-Poisson and CAT-GTR (Lartillot and Philippe 2004). Two independent MCMC chains were run under the CAT-GTR model, and four independent MCMC chains were run under the CAT-Poisson model. The CAT-GTR and CAT-poisson models did not converge after a long CPU time, and only the results from the CAT-poisson model are included here.

Morphological character data were obtained from the literature, or from direct observation of available voucher material.

Subsequent analyses were conducted in R and integrated into this manuscript with the `knitr` package. See Supplementary Information for R package version numbers.

Hypothesis testing

Results and Discussion

Sample collecting and sequencing

Species phylogeny

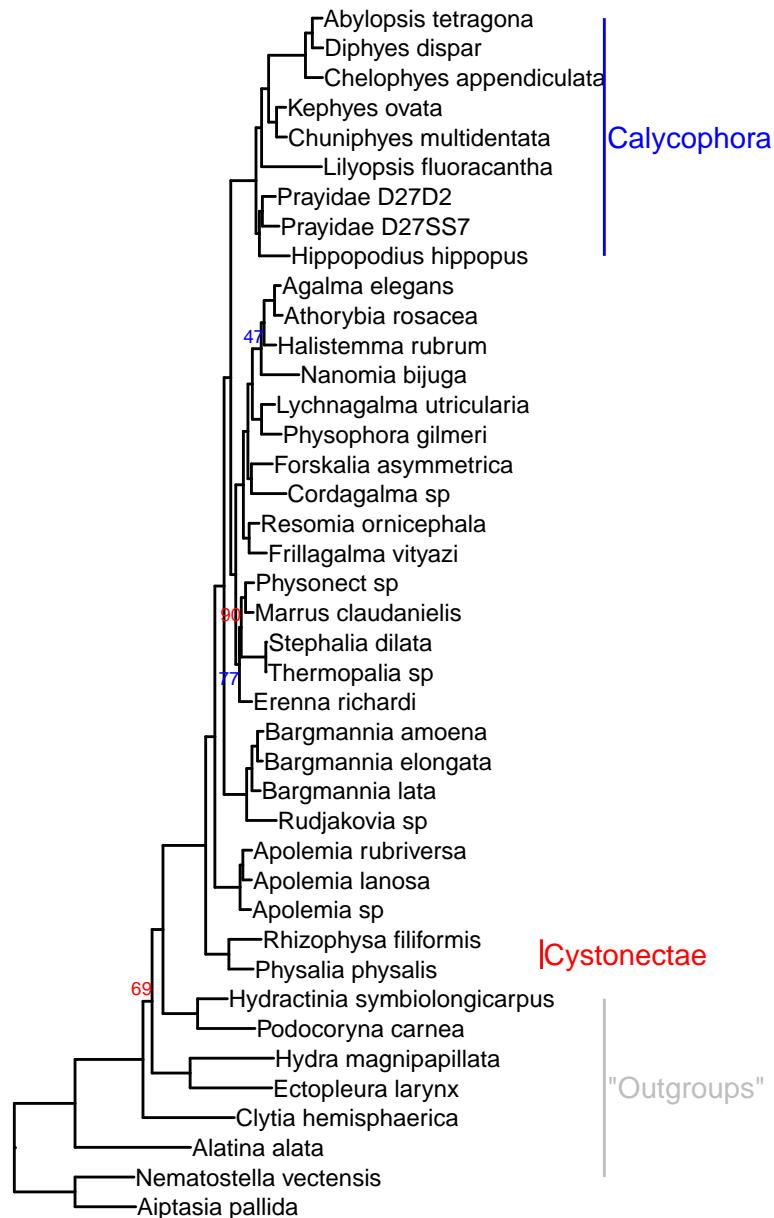


Figure 2: Phylogram of siphonophore relationships. Node labels indicate bootstrap support percent, unnumbered nodes have 100% support. The image was rendered with ggtree (Yu et al. 2016)

(XX This paragraph on sampling through *Agalma* analyses) The analyses presented here consider XXX siphonophore species and 8 outgroup species. This includes new data for XXX species. Summary stats on assemblies XX (Table XX). Matrix has XX genes, XX sites, and occupancy is XX.

(XX This paragraph summarizes phylogeny runs, apart from tree topology) Maximum likelihood analyses had 1000 replicates. We ran 4 phylobayes chains, and visual inspection of the traces indicated that a burn in of 400 trees was sufficient for all runs. This left 15847 trees in the posterior. XXConvergence...

These findings are entirely consistent with a previous analysis based on two genes (16S and 18S ribosomal RNA) (Dunn et al. 2005). Cystonectae is the sister group to the remaining siphonophores, and Calyphorae is nested within the paraphyletic “Physonectae”. In addition, multiple nodes that were not resolved in the previous two-gene analysis do receive strong support in this 1,071-gene transcriptome analysis. These findings include XXX.

Character Evolution

Siphonophores have evolved a fascinating diversity of morphological features, zooid types, life history traits, and habitats. Here we explore the evolutionary history of some of these features.

In our previous siphonophore phylogenetic analysis (Dunn et al. 2005) there were several characters left with equivocal evolutionary histories, due to unresolved relationships between physonects. With our current cladistic resolution, we were able to answer some of the questions left open:

Evolution of Monoecy

[Citation needed] noticed for the first time that some siphonophores were monoecious and others were dioecious. Our analyses in 2005 reconstructed this character and found a great amount of phylogenetic conservatism, with an unambiguous resolution of the MRCA (most recent common ancestor) as dioecious, and the appearance of monoecy in several taxa and clades (including Calyphorae) within the polytomy. Figure X shows the evolution of sex distribution in siphonophores under the current better-resolved tree model, and it strongly indicates that monoecy in siphonophores from a dioecious ancestor occurred twice, in the branch leading to Calyphorae and in the branch leading to Agalmatids (*sensu lato*). There is a small probability for an alternative scenario featuring a single gain of monoecy before the split of Calyphorae, with a subsequent derived shift back to dioecy in the *Marrus-Erenna* clade.

The Evolution of Zooid Types

One of the most striking aspects of siphonophore biology is their diversity of unique zooid types. Other colonial cnidarians (such as Hydractinia) and some bryozoans (example) have been found to have up to X different zooid types [Citation1, Citation 2]. The siphonophore genus *Forskalia* has 6 basic zooid types (pneumatophore, nectophore, gastrozooid, palpon, bract, and gonophore), and a total of 10 counting subtypes (4 types of bract, male & female gonophores). Diphyomorphs have more than 1 type of nectophore, while Cystonects have none. Here we reconstruct the evolutionary origins of the different zooid types on the present transcriptome tree.

Nectophores are retained modified medusae that Codonophora use for coordinated colony-level swimming. The nectosoma is the region of the colony that develops from the nectosomal growth zone. Unlike the siphosomal growth zone, the nectosoma does not bud gastrozooids, but nectophores (and in the case of *Apoemia*, also palpons). In fact, with the exception of *Physalia physalis* (which grows small nectophores near the gonodendra), siphonophore nectophores are exclusively found on the nectosoma. It is possible that the MRCA of siphonophores had a nectosoma, which has lost on the branch leading to Cystonects. We cannot exclude with certainty the alternative hypothesis of a nectosoma-less ancestor followed by a gain of the nectosoma in the branch leading to the Codonophora. The nectosoma probably arose as a duplication of the siphosoma, followed by functional specialization in propelling the colony. The nectosoma has been lost within Codonophora in the genus *Athorybia*.

Following the colony development orientation framework presented in (citation), the nectosoma can be located in a dorsal or a ventral position. Our ancestral reconstructions for this character (Supp figure) show that

a ventrally-oriented nectosome was the ancestral form in siphonophores, and that a dorsal nectosome has evolved twice independently, in the branches leading to the Agalmatidae (sensu stricto) and the branch leading to the *Bargmannia* species. All Codonophora (with the exception of *Athorybia* species) have a nectosome, but the number and subtypes of nectophores present varies greatly between species. As shown in Figure X, most Codonophora presents the ancestral nectosome with multiple nectophores of the same subtype. However, Calyctophorans evolved a different system with just 2 nectophores of one type. This shift may be associated with the loss of the pneumatophore. Not all Calyctophorans remained with this arrangement. The Hippopodidae returned to bearing multiple identical nectophores, many of which are inactive and serve functions of defense (like a shell to retract in) and buoyancy. As in the rest of Calyctophorans, the Hippopodids only use 2 nectophores to propel the colony. Another interesting shift occurs in the branch leading to Diphyomorpha, where the 2 nectophores specialize into 2 subtypes, associated with a shift into a vertically aligned position and pointed bell shapes. The 2 types function together in a coupled hydrodynamic system that allows very fast escape responses (Mackie 1964).

Bracts are highly reduced zooids unique to siphonophores, but they are only present in the Codonophora. As with the nectosome, we have ambiguity determining whether the MRCA of siphonophores had bracts or not. The MRCA of Codonophora had only one bract subtype, which was lost in Hippopodidae and in *Gymnopræia lapislazula*. Bracts are functional for protection of the delicate zooids and to help maintain neutral buoyancy. Some calyctophorans are able to actively exclude sulphate ions in their bracts to adjust their buoyancy along the colony (Bidigare, R. R., & Biggs, D. C. (1980).

The ancestral siphonophore certainly had a pneumatophore (Supp Figure X). This unique zooid fills itself with gas, which helps the colony float and maintain its orientation in the water column. Recent evidence of neural arrangement in the pneumatophore of *Nanomia bijuga* (Church, 2013) suggests it could also gather information on relative pressure changes (and thus depth changes), helping regulate geotaxis. Despite its multiple biological functions, it was lost in the Calyctophorae and never gained again in that clade. Calyctophorans rely on the ionic balance of their gelatinous nectophores and bracts to retain posture and neutral buoyancy.

Palpons are modified mouthless gastrozooids used for digestion and circulation of the gastrovascular fluid. They were present in the MRCA of siphonophores (Supp Figure X), retained in most species, but lost twice independently in the branches leading to *Bargmannia* and Calyctophorae. These taxa might have found other avenues to effectively circulate nutrients across the colony.

The Gain and Loss of Tentilla

The most complex nematocyst batteries of Cnidaria can arguably be found among the siphonophores, hanging in regularly spaced tentacle side branches called tentilla. Most hydrozoans, including the clade that contains siphonophores, bear simple tentacles (tentacles with no side branches). It is still an open question whether the MRCA of Siphonophora had simple or branched tentacles. The only siphonophore genera regarded as lacking tentilla are *Physalia physalis* and *Apolemia* spp., and *Bathypheysa conifera*. Since *B. sibogae* is the only member of the *Rhizophysidae* (and of the *Bathypheysa* genus) lacking tentilla, we can safely assume this is a case of secondary loss. When we reconstruct the evolution of this character on the current phylogeny, we find that 70% of simulations support an MRCA bearing tentilla, with two independent losses leading to *Physalia* and *Apolemia*. However, this leaves a 30% support for a simple-tentacled MRCA followed by 2 independent gains of tentilla in the branches leading to *Rhizophysidae* and *{Bargmannia, Diphyes}*.

A key issue here is how we code for absence of tentilla, especially for the case of *Physalia physalis*. The tentacles of this species, when uncoiled, show very prominent, evenly spaced, bulging buttons which contain on their ectoderm all active and functionally arranged nematocysts used by the organism for prey capture. Siphonophore tentilla are complete diverticular branchings of the tentacle ectoderm, mesoglea, and gastrovascular canal (lined by endoderm). Hessinger & Ford 1988 (in the Biology of Nematocysts) described *Physalia*'s buttons as enclosing individual fluid-filled chambers connected by narrow channels to the tentacular canal, lined by endoderm. This suggests they are not just ectodermal swellings, but probably are reduced tentilla. When we code *Physalia physalis* as tentilla bearing, the results for the character reconstruction lead to a

more robust support for a tentilla-bearing MRCA followed by a single loss of tentilla in the branch leading to *Apolemiidae* (Figure 5b).

Siphonophore tentilla present an astounding diversity of sizes, shapes, colors, and nematocyst complements, and some have been observed to rapidly uncoil in contact with prey. Future research should explore the evolutionary history of these unique structures.

The Evolution of Vertical Habitat Use

Siphonophores are abundant predators in the pelagic realm, ranging from the surface (*Physalia physalis*) to bathypelagic depths (ref , *Bargmannia* sp 3888m VARS unpublished). While there are some pleustonic (*Physalia*) and benthic (*Rhodaliidae*) siphonophores, the phylogeny suggests the siphonophore MRCA was planktonic, as most extant taxa are. Some interesting questions arise from these facts, including 1) what was the bathymetric niche of the siphonophore MRCA, and 2) how did siphonophore's vertical habitat use of the water columns evolve along the phylogeny. Our results indicate a mesopelagic MRCA, with several convergent transition events to epipelagic and bathypelagic waters. There was only a single transition to benthic lifestyle on the stem of *Rhodaliidae*.

Discussion

The strong phylogenetic signal in the characters traditionally used for taxonomic diagnostics is a positive indicator of the applicability and unambiguity of these characters.

Conclusions

Acknowledgements

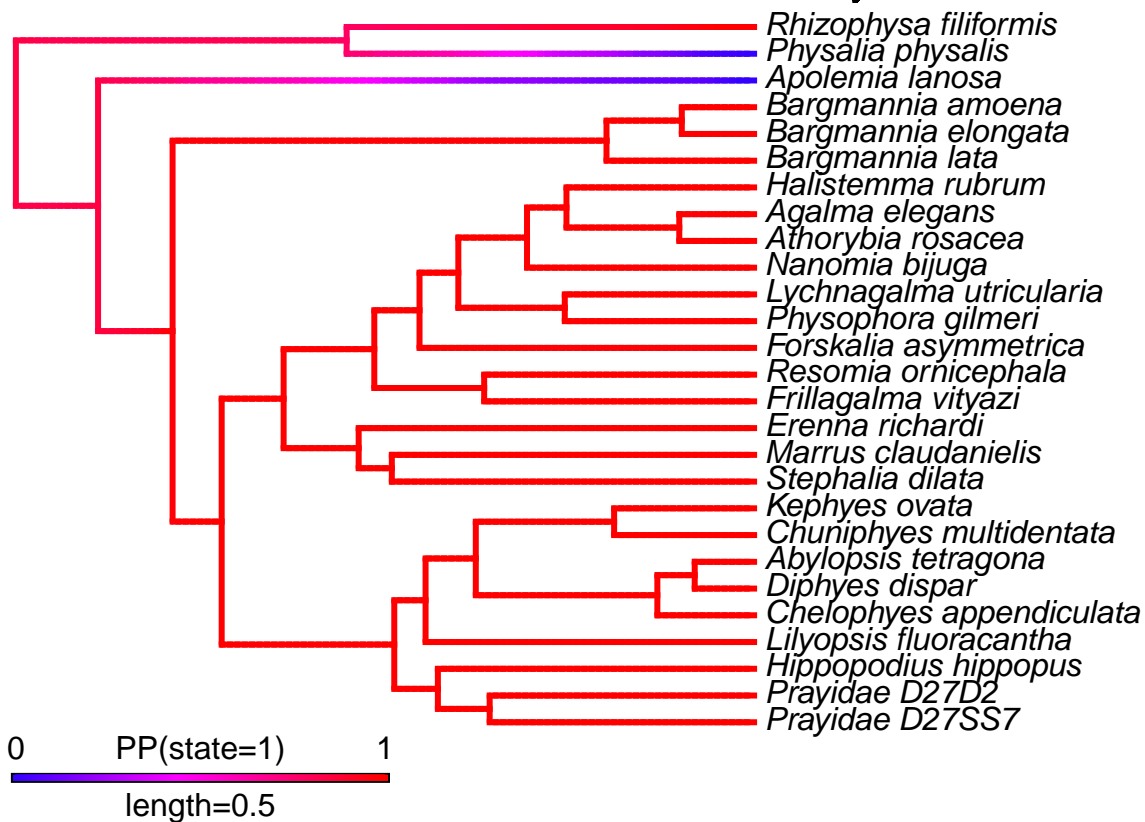
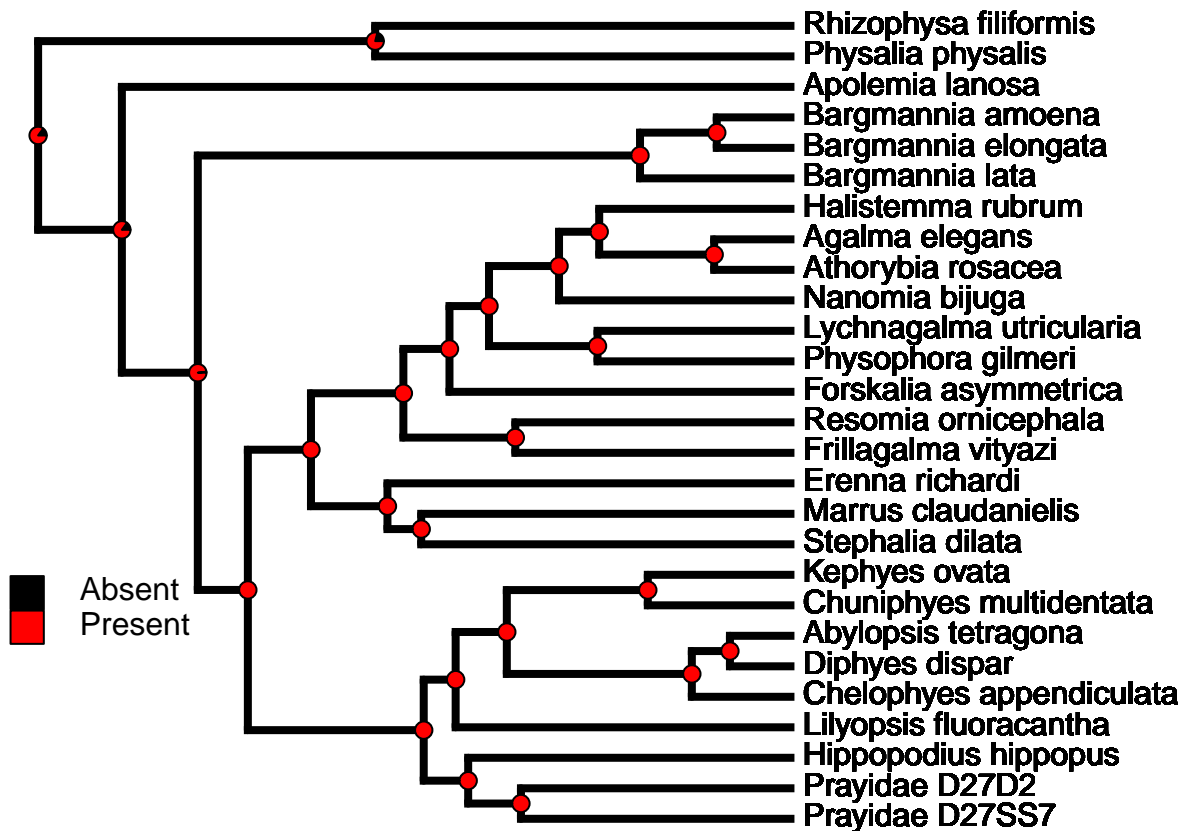
This work was supported by the National Science Foundation (DEB-1256695 and the Waterman Award). Sequencing at the Brown Genomics Core facility was supported in part by NIH P30RR031153 and NSF EPSCoR EPS-1004057. Data transfer was supported by NSF RII-C2 EPS-1005789. Analyses were conducted with computational resources and services at the Center for Computation and Visualization at Brown University, supported in part by the NSF EPSCoR EPS-1004057 and the State of Rhode Island. We also thank the MBARI crews and ROV pilots for collection of the specimens.

Supplementary Information

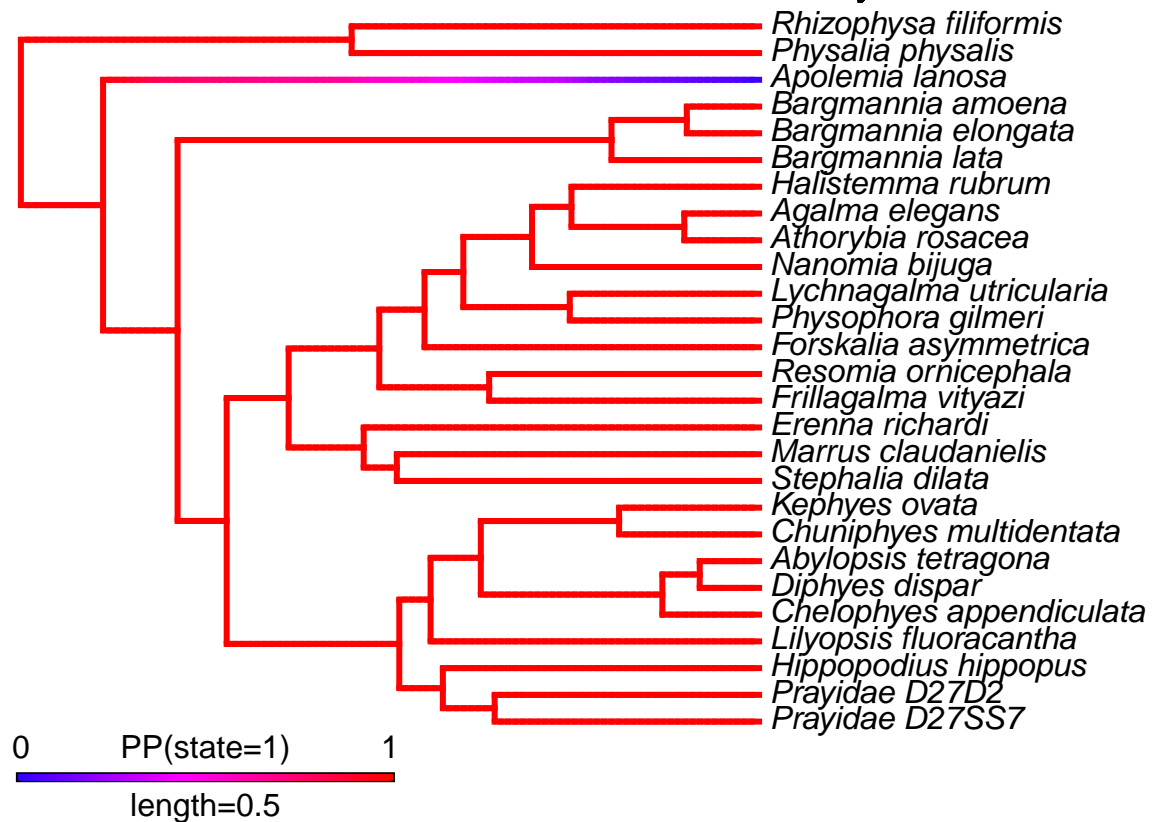
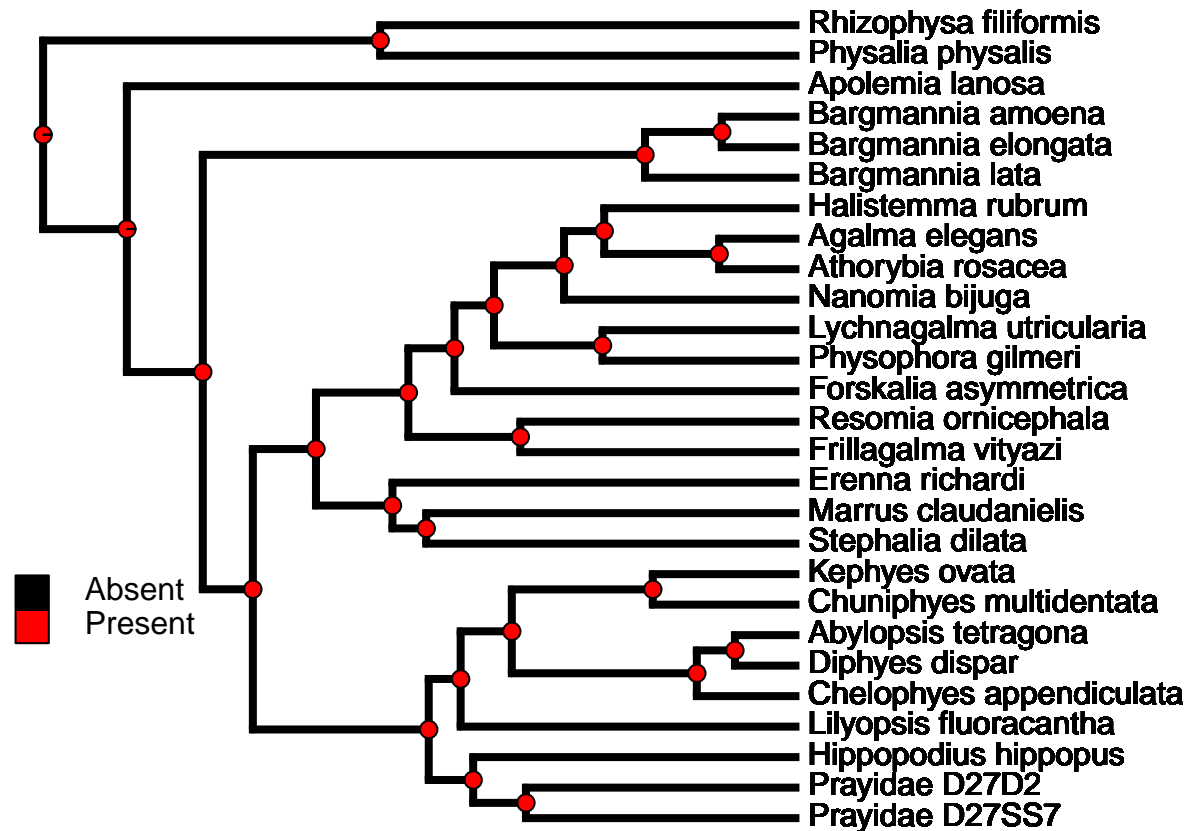
% latex table generated in R 3.4.1 by xtable 1.8-2 package % Fri Nov 3 16:00:19 2017

Table 1 (at the end of file): Summary statistics for libraries.

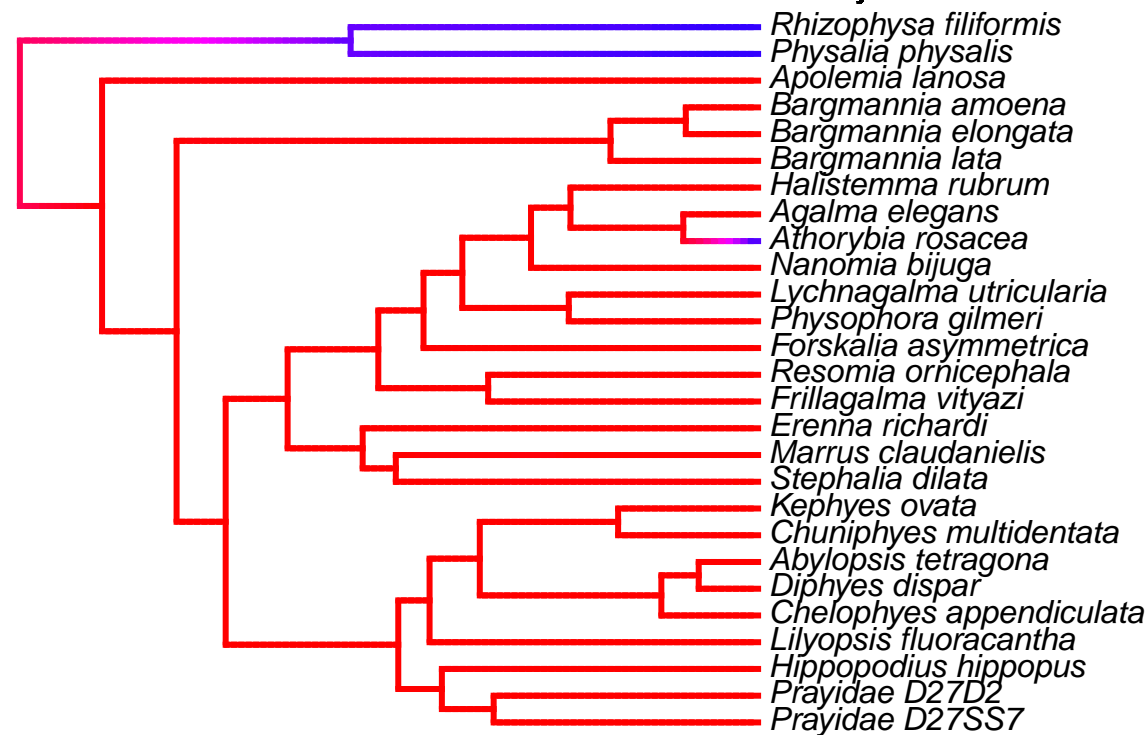
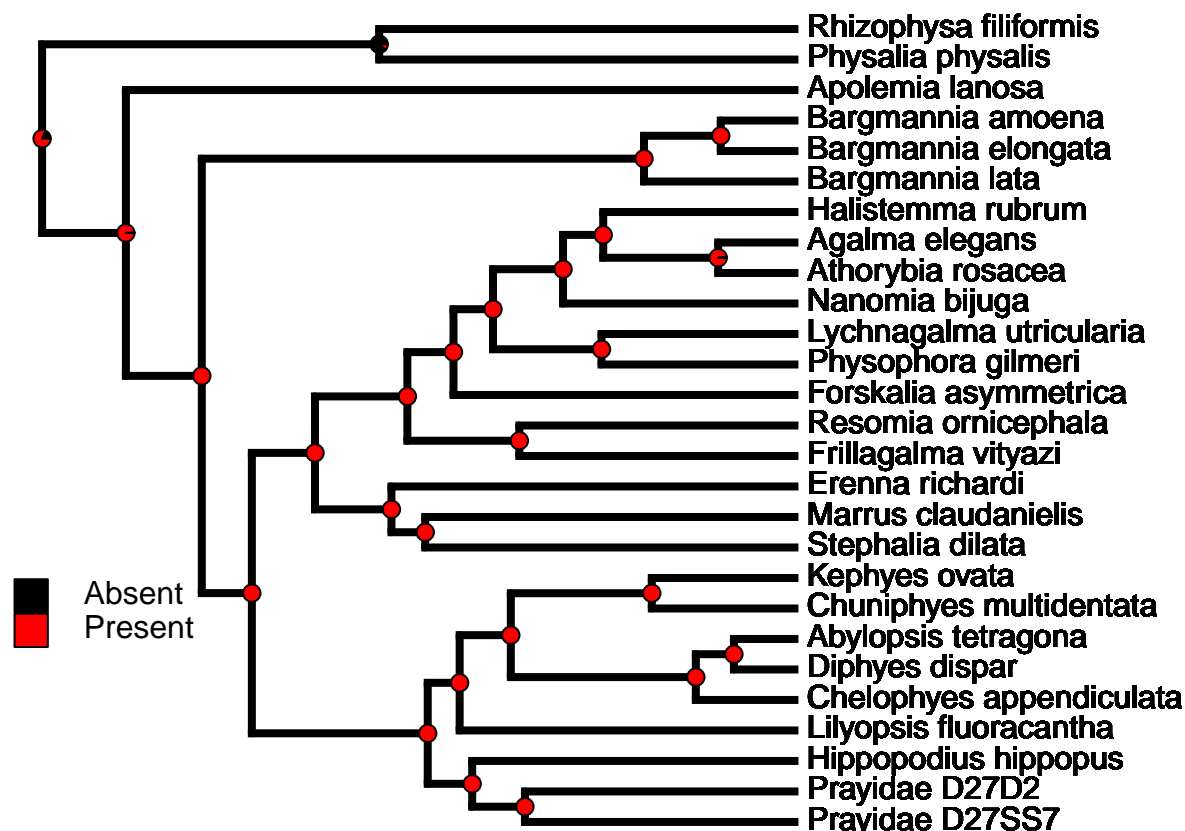
SIMMAP Presence of tentilla



SIMMAP Presence of tentilla - *Physalia* corrected



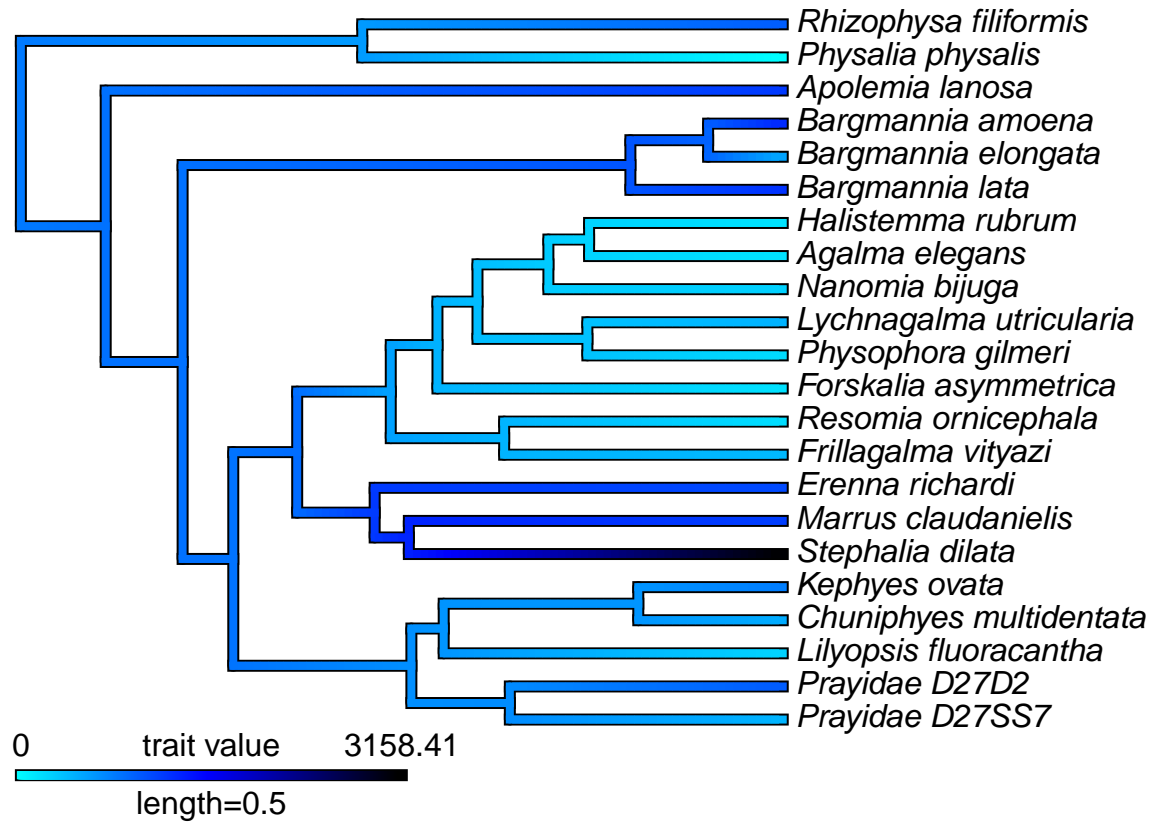
SIMMAP Presence of Nectosome



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 probabilities of states (1 Present, 0 Absent).

Posterior

Median depth reconstruction:



Phylogenetic signal in the character data

Phylogenetic signal in Binary Traits

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## \hline
## Nectosome & 0.7576982 & 0.20867575 & 0.4735495 & 0.2605 & -0.6017493 \\
## Palpons & 2.6719102 & 0.12030122 & 1.2998920 & 0.0010 & -1.9610733 \\
## Tentilla & 2.9207926 & 0.06470251 & 0.6092236 & 0.0010 & -1.1260604 \\
## Pneumatophore & 3.9936316 & 0.06932454 & 1.0983657 & 0.0010 & -1.7715626 \\
## Bracts & 1.8939427 & 0.08917691 & 0.4449703 & 0.0020 & -0.8537939 \\
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Software versions

This manuscript was computed on Wed Nov 22 09:54:13 2017 with the following R package versions.

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Running under: macOS Sierra 10.12.2

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References

- Beklemishev W.N. 1969. Principles of comparative anatomy of invertebrates. Edinburgh:Oliver & Boyd.
- Carré C. 1967. Le developpement larvaire d'Abylopsis tetragona. Cahiers de Biologie Marine. 8:185–193.
- Carré C., Carré D. 1991. A complete life cycle of the calycophoran siphonophore muggiaea kochi (will) in the laboratory, under different temperature conditions: Ecological implications. Philosophical Transactions of the Royal Society of London B: Biological Sciences. 334:27–32.
- Carré C., Carré D. 1995. Trait e de zoologie. anatomie, systématique, biologie. Paris:Masson.
- Carré D. 1969. Etude histologique du developpement de nanomia bijuga (chiaje, 1841), siphonophore physonecte, agalmidae. Cahiers de Biologie Marine. 10:325–341.
- Cartwright P., Nawrocki A.M. 2010. Character evolution in hydrozoa (phylum cnidaria). Integrative and

Comparative Biology. 50:456–472.

Dunn C., Pugh P., Haddock S. 2005. Molecular Phylogenetics of the Siphonophora (Cnidaria), with Implications for the Evolution of Functional Specialization. *Systematic biology*. 54:916–935.

Dunn C.W., Howison M., Zapata F. 2013. Agalma: an automated phylogenomics workflow. *BMC Bioinformatics*. 14:330.

Dunn C.W., Wagner G.P. 2006. The evolution of colony-level development in the siphonophora (cnidaria: Hydrozoa). *Development genes and evolution*. 216:743–754.

Lartillot N., Lepage T., Blanquart S. 2009. PhyloBayes 3: A bayesian software package for phylogenetic reconstruction and molecular dating. *Bioinformatics*. 25:2286–2288.

Lartillot N., Philippe H. 2004. A bayesian mixture model for across-site heterogeneities in the amino-acid replacement process. *Molecular Biology and Evolution*. 21:1095–1109.

Mackie G., Pugh P., Purcell J. 1988. Siphonophore biology. *Advances in marine biology*. 24:97–262.

Pugh P. 1983. Benthic siphonophores: A review of the family rhodaliidae (siphonophora, physonectae). *Philosophical Transactions of the Royal Society of London, B*. 301:165–300.

Studies on physalia physalis (l.). part 1. natural history and morphology *Discovery Reports*. 30:301–368.

Totton A.K., Bargmann H.E. 1965. A synopsis of the siphonophora. *British Museum (Natural History)*.

Yu G., Smith D.K., Zhu H., Guan Y., Lam T.T.-Y. 2016. ggtree: an r package for visualization and annotation of phylogenetic trees with their covariates and other associated data. *Methods in Ecology and Evolution*.

| Species | Mean insert size (bp) | Insert size standard deviation | Number of read pairs | Percent kept after rRNA removal | Percent kept after assembly | Adapter fails | Quality fails | Base Composition fails | Total assembled transcripts | Coding transcripts |
|-------------------------------|-----------------------|--------------------------------|----------------------|---------------------------------|-----------------------------|---------------|---------------|------------------------|-----------------------------|--------------------|
| Marrus claudanielis | 253.03 | 53.30 | 35866092 | 96.8 | 62.1 | 113298 | 15594637 | 4981676 | 105439 | 22511 |
| Apolemia rubriversa | 290.81 | 80.64 | 19228660 | 91.7 | 77.8 | 40594 | 5179800 | 516100 | 87701 | 17540 |
| Chuniphyces multidentata | 284.46 | 35.74 | 17999147 | 77.0 | 74.3 | 24263 | 4941872 | 335297 | 84341 | 22084 |
| Apolemia sp | 167.41 | 53.46 | 16761717 | 81.3 | 79.4 | 1332063 | 3062035 | 41943 | 51470 | 14752 |
| Apolemia lanosa | 167.74 | 55.30 | 18444476 | 96.4 | 80.9 | 923922 | 3882968 | 439569 | 70184 | 15579 |
| Bargmannia elongata | 271.43 | 40.17 | 40008913 | 79.8 | 78.5 | 342825 | 8084832 | 2017709 | 152019 | 23661 |
| Diphyes dispar | 223.14 | 58.73 | 80000000 | 78.7 | 63.4 | 14412120 | 21322624 | 690159 | 210406 | 50868 |
| Aiptasia pallida | 183.18 | 53.88 | 74558341 | 98.4 | 79.3 | 210730 | 23826421 | 307520 | 83950 | 33523 |
| Stephalia dilata | 267.82 | 43.33 | 30953585 | 98.0 | 63.9 | 86068 | 15731787 | 1435119 | 107925 | 23984 |
| Physalis physalis | 233.10 | 54.37 | 36481773 | 96.6 | 88.5 | 18553 | 5491979 | 259497 | 74994 | 23705 |
| Bargmannia amoena | 261.57 | 53.77 | 20195498 | 84.6 | 80.1 | 1049110 | 3996085 | 274520 | 66726 | 17975 |
| Frillagalma vityazi | 283.11 | 44.91 | 79902051 | 54.0 | 70.4 | 668400 | 13591301 | 5558767 | 181508 | 29293 |
| Alatina alata | 173.96 | 60.33 | 96259870 | 52.1 | 77.9 | 1236251 | 15771112 | 468662 | 166584 | 28743 |
| Clytia hemisphaerica | | | | | | | | | 11476 | 6642 |
| Ectopleura larynx | 229.05 | 37.75 | 109024653 | 95.9 | 74.6 | 432309 | 40629127 | 897590 | 84034 | 28015 |
| Athorybia rosacea | 221.16 | 93.65 | 28696930 | 99.9 | 86.9 | 691916 | 4026467 | 633700 | 100839 | 24543 |
| Forskalia asymmetrica | 259.42 | 35.04 | 25275184 | 58.9 | 65.1 | 41922 | 7463840 | 841930 | 82483 | 18419 |
| Prayidae D27D2 | 267.32 | 45.59 | 38233199 | 85.2 | 66.4 | 59773 | 15338562 | 1878732 | 144909 | 28065 |
| Lilyopsis fluoracantha | 259.39 | 39.08 | 51855968 | 76.5 | 65.3 | 72416 | 19809124 | 1388875 | 114662 | 29854 |
| Hydractinia symbiolongicarpus | 175.22 | 57.84 | 60462724 | 49.8 | 85.2 | 162430 | 6678373 | 124392 | 71450 | 24639 |
| Rhizophysa filiformis | 269.74 | 46.52 | 26937827 | 92.5 | 65.3 | 66010 | 13238701 | 361376 | 110109 | 24833 |
| Agalma elegans | 238.94 | 57.54 | 40007833 | 99.6 | 86.0 | 31957 | 7177806 | 748977 | 122053 | 26601 |
| Chelophyes appendiculata | 275.93 | 39.43 | 21103284 | 89.0 | 74.2 | 63548 | 6777022 | 344708 | 110612 | 32309 |
| Prayidae D27SS7 | 303.39 | 50.83 | 25233164 | 66.7 | 65.6 | 39061 | 8616289 | 347189 | 94917 | 24211 |
| Rudjakovia sp | 213.88 | 89.71 | 20582477 | 99.1 | 79.7 | 489520 | 3936086 | 1546686 | 91695 | 24184 |
| Abylopsis tetragona | 292.16 | 38.32 | 21575176 | 73.3 | 73.8 | 38764 | 5759144 | 370604 | 102946 | 25268 |
| Nematostella vectensis | | | | | | | | | 26511 | 18080 |
| Hippopodius hippopus | 266.99 | 45.11 | 35638254 | 84.5 | 66.3 | 56152 | 15490291 | 535026 | 137341 | 35031 |
| Physophora gilmeri | 214.97 | 93.78 | 19847377 | 99.3 | 81.3 | 936617 | 3464079 | 1007839 | 52639 | 17381 |
| Bargmannia lata | 266.71 | 62.80 | 16984483 | 98.7 | 71.1 | 3118496 | 4227140 | 868584 | 59051 | 16451 |
| Nanomia bijuga | 296.69 | 44.20 | 39983229 | 85.7 | 75.15 | 155093 | 10854240 | 795226 | 165792 | 28927 |
| Erenna richardi | 291.53 | 36.76 | 29776547 | 64.2 | 66.6 | 39775 | 8958200 | 1245523 | 89423 | 18236 |
| Physonect sp | 261.09 | 35.96 | 38243543 | 24.3 | 66.7 | 12494 | 4517982 | 274838 | 57746 | 12596 |